Working Report 2007-39

Landscape Modelling Case Studies for Olkiluoto Site in 2005-2006

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May 2007

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ABSTRACT

This report documents the landscape modelling test cases implemented in the fall of 2005, complemented in 2006. The objective of the report is to illustrate the application of the landscape modelling methodology, to investigate the important factors of influence and to clarify methodological aspects. The results of this analysis are intended to serve as a basis for future assessments.

Landscape modelling represents an approach for estimating doses to inhabitants of a landscape consisting of several interacting ecosystems which are affected by the contamination from potential radionuclide releases from a deep geological repository. From the model outputs, Landscape Dose Conversion Factors (LDFs) are calculated. These represent, for each radionuclide of concern, an estimate of the equilibrium dose arising from a constant unit release of activity into the landscape objects. Modelling is undertaken in the current report for static landscapes corresponding to future landscape configurations forecasted for four different points in time.

The results of this modelling are not yet suitable for practical application to estimate doses which could result from the planned repository at the Olkiluoto site. To suit this eventual purpose, refinements of the modelling and reduced uncertainty of the important parameters used in the models will be necessary. The current report intends rather to investigate the important factors influencing modelled future doses arising from the planned repository and to clarify methodological aspects.

Notwithstanding the restrictions of the current modelling, important conclusions already can be drawn from the results presented in this report. Several methodological aspects are addressed in this report. These are, in particular, the impact of the landscape configurations on the resulting dose estimates, the importance of model parameters and assumptions for the assessment results, the database for radionuclides requiring consideration, the importance of the accumulation of radionuclides in certain landscape objects, the importance of different release points and their spatial distribution and the effects of boundary conditions for the release (geosphere-biosphere interface).

Conclusions derived with regard to these issues in the current report will require to be reviewed based on results obtained with improved models and data. In particular, it will have to be investigated what effect a dynamic change of the landscape as opposed to the static consideration in this report has on the derived conclusions. Despite this necessity for review, it is believed that the derived conclusions will remain valid at least qualitatively.

Keywords: biosphere assessment, radionuclide transport, sensitivity analysis, dose, landscape dose conversion factor

Olkiluodon biosfäärin alueellisia kulkeutumismallitarkasteluja 2005-2006

TIIVISTELMÄ

Tässä raportissa esitetään syksyllä 2005 tehtyjen ja vuoden 2006 aikana täydennettyjen biosfäärin alueellisten kulkeutumismallitarkastelujen keskeiset tulokset. Raportin tarkoitus on havainnollistaa alueellisen kulkeutumismallinnusmenetelmän soveltamista, selventää menetelmällisiä yksityiskohtia ja tutkia tuloksiin vaikuttavia tekijöiden keskinäistä merkitystä. Työn tuloksien perusteella parannetaan tulevia biosfääriarviointeja.

Alueellisessa kulkeutumismallinnuksessa arvioidaan useiden toisiinsa vaikuttavien ekosysteemien muodostamalla ja mahdollisten loppusijoitustilasta vuotavien radionuklidien kontaminoimalla alueella asuvien henkilöiden mahdollisesti saamia säteilyannoksia. Laskennan lopputuloksista voidaan edelleen laskea alueelliset annosmuunnoskertoimet (LDF, Landscape Dose conversion Factor), jotka edustavat kustakin tarkasteltavasta radionuklidista tasapainotilassa aiheutuvaa säteilyannosta jatkuvaa yksikköpäästöä kohti. Tässä raportissa tarkastellaan ajallisesti muuttumattomia alueita, jotka edustavat ennustettuja Olkiluodon ympäristön maastonmuotoja ja ekosysteemejä neljällä eri ajanhetkellä tulevaisuudessa.

Tarkastelujen tuloksena saadut säteilyannokset eivät sinänsä ole vielä sopivia Olkiluotoon suunnitellun käytetyn ydinpolttoaineen loppusijoitustilan annosvaikutusten arviointiin. Tätä tarkoitusta varten tarvitaan vielä paitsi ekosysteemikohtaisten kulkeutumismallimoduulien parantamista myös tarkempia tietoja tärkeimmistä mallien syöttötiedoista. Tämä raportti pyrkiikin osoittamaan lopputuloksiin eniten vaikuttavia tekijöitä ja selventämään menetelmän soveltamiseen liittyviä erityiskysymyksiä, jotta jatkotyö voidaan suunnata merkittäviin seikkoihin tehokkaasti.

Näiden tarkastelujen rajoittuneisuudesta huolimatta tässä raportissa esitetyistä tuloksista voidaan kuitenkin tehdä useita merkittäviä johtopäätöksiä valitun maasto- ja ekosysteemikokonaisuuden vaikutuksesta annoksiin, mallien parametrien ja oletusten vaikutuksesta lopputuloksiin, merkittävien radionuklidien joukosta, radionuklidien kertymisestä tiettyihin paikkoihin ja sen merkityksestä lopputuloksien kannalta sekä lähdetermin määrittelyn merkityksestä koskien päästöpisteiden jakautumaa ja sijaintia suhteessa mallinnuslokeroihin (geosfääri-biosfäärirajapinta). Nämä johtopäätökset tulee kuitenkin vielä varmistaa parannettujen mallien ja syöttötietojen perusteella. Erityisesti tulevaisuudessa on tarkasteltava maaston ja ekosysteemien dynaamisen muutoksen ja nyt käsiteltyjen muuttumattomien tilanteiden välisiä eroja ja mahdollisia vaikutuksia lopputuloksiin ja johtopäätöksiin. Huolimatta jatkoselvitystarpeista, tässä raportissa esitettyjen johtopäätösten uskotaan pysyvän paikkansapitävinä jatkossakin vähintään laadullisesti.

Avainsanat: biosfääriarviointi, radionuklidien kulkeutuminen, herkkyystarkastelu, annos, alueellinen annosmuunnoskerroin

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ABSTRACT

TIIVISTELMÄ

1 INTRODUCTION

Spent fuel from the Finnish nuclear power reactors is planned to be disposed of in a KBS-3 type repository to be constructed at a depth between 400 and 600 metres in the crystalline bedrock at the Olkiluoto site.

The Finnish Parliament ratified in 2001 the Government's favourable Decision in Principle on Posiva's application to locate the repository at Olkiluoto. This decision represents the milestone prior to entering the phase of confirming site characterisation. The next step of the nuclear licensing of the repository is the application for the construction license in 2012. The required documentation of studies and conclusions on the long-term safety will be published in three main steps with an increasing level of detail (Vieno & Ikonen 2005):

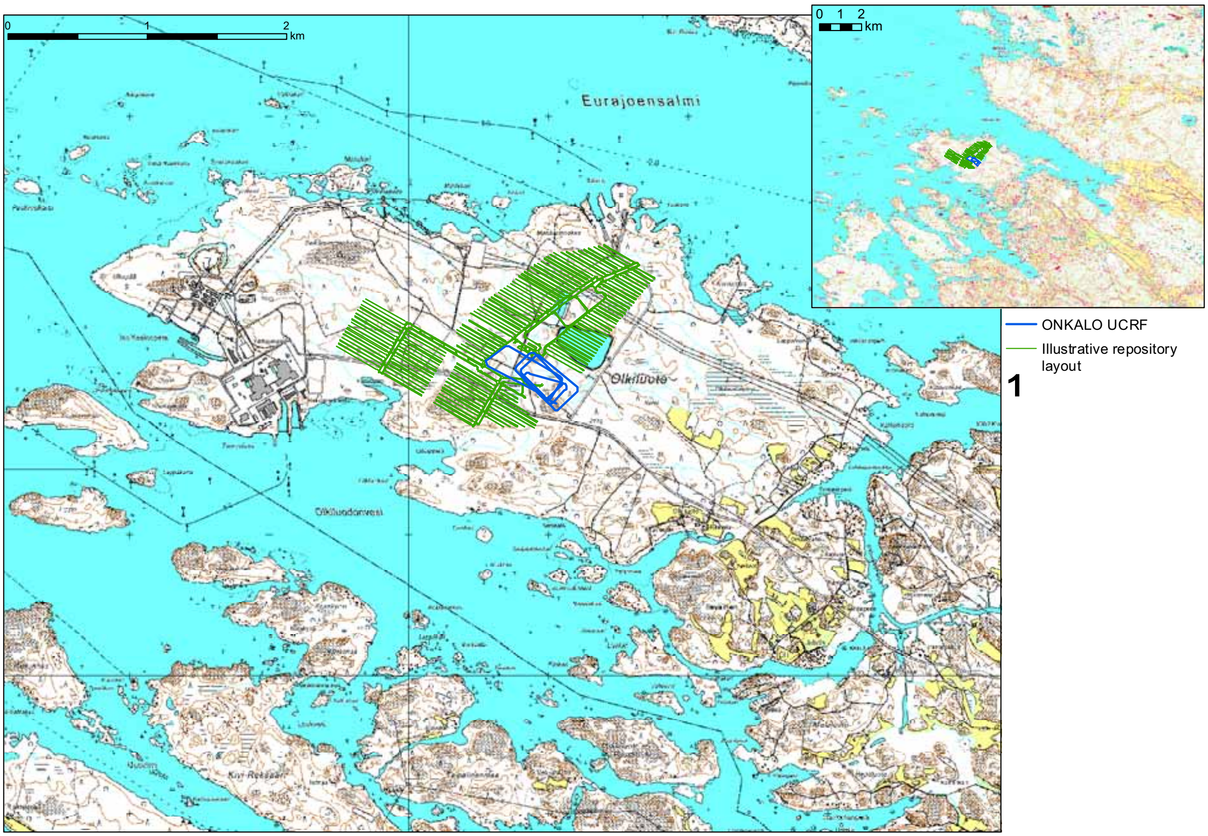
- interim reporting of studies on the long-term safety in 2006,
- outline and preliminary assessments of the Preliminary Safety Analysis Report (PSAR) in 2009, and
- construction license application supported by the full PSAR by 2012.

A plan for a synthesis of evidence, analyses and arguments that quantify and substantiate the safety and the level of expert confidence in the safety, i.e. the safety case, was prepared in 2004 (Vieno & Ikonen 2005). The planning report introduces the Posiva Safety Case Portfolio as the documentation management approach, facilitating flexible and progressive development of the safety case. In the portfolio, biosphere assessment is one of the main components, which is further outlined in the planning report. The assessment of the biosphere is planned to be compiled on the basis of several modelling and other reports documenting the models and data in detail (Ikonen 2006).

1.1 Olkiluoto site

Olkiluoto is a large island (approx. 12 km2), separated from the mainland by a narrow strait, on the coast of the Baltic Sea. The Olkiluoto nuclear power plant with two reactors in operation, and the VLJ repository for low- and intermediate-level waste are located in the western part of the island. The construction of a new reactor unit (OL3) is underway at the site. The repository for spent fuel will be constructed in the central part of the island (Figures 1 and 2) after the construction license procedures for a nuclear facility has been completed (application planned for 2013). Construction of an underground rock characterisation facility, called ONKALO, was started in June 2004.

Olkiluoto is located in the area of significant postglacial land uplift (currently about 6 mm/y; Mäkiaho 2005). This leads to new land areas emerging continuously. This process is accelerated by a rather flat topography and eutrophication of the shallow bays. In the archipelago area south-southwest of Olkiluoto, relatively early emergence of smaller-scale lake and river systems is expected. Another important factor for the development of the landscape is a large river (Eurajoki), which has its outlet northeast of the island. It is expected that this river will flow north of the planned repository in the future. This will affect the mass balances within the region by erosion and sedimentation processes significantly.



Basemaps (c) National Land Survey, permission 41/MYY/05

Figure 1. *Olkiluoto Island and its surroundings. An example of an illustrative repository layout is shown in green and the ONKALO underground characterisation and research facility currently in construction in blue lines.*

Figure 2. *Aerial photos over the Olkiluoto area: left, western end of the island with the power plant and part of the southern archipelago; right, Olkiluoto island seen from the east (photos: Helifoto Oy, 2005).*

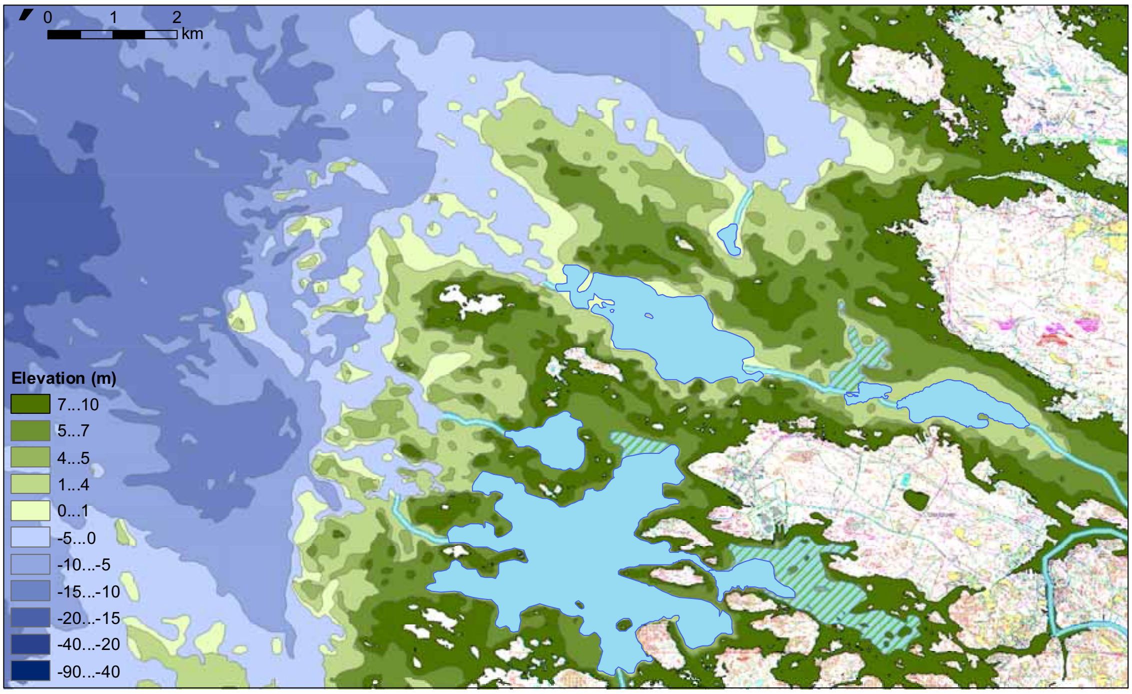


Figure 3. *A possible map of the Olkiluoto site about 2000 years after present (10 m land uplift, omitting changes in sea level due to climate change).*

Figure 4. *A possible map of the Olkiluoto site about 5900 years after present (25 m land uplift, omitting changes in sea level due to climate change).*

The expected future development of the landscape at the site is illustrated in Figures 3 and 4. These show maps which have been prepared based on the current topography and simple assumptions of an evenly distributed land uplift rate slightly decreasing with time (Löfman 1999, p. 40-41) and of no changes in sea level. It becomes evident that significant changes in the ecosystem types during the biosphere assessment timeframe are to be expected.

1.2 Safety Case and Biosphere Assessment Portfolio

The Posiva Safety Case portfolio was introduced in the Safety Case Plan of 2004 (Vieno & Ikonen 2005). Its main ideas are summarised here, but for a comprehensive picture of the whole Posiva Safety Case, the reader is advised to see the Safety Case Plan.

1.2.1 Principles of Safety Case

First the purpose and context of the safety case should be made clear and the overall safety strategy presented. This includes strategies for siting, design and implementation of the repository as well as the strategy for performing safety assessments (Vieno & Ikonen 2005).

The information and analysis tools for safety assessment must be described. These are collectively termed the assessment basis, and include

- the system concept – that is a description of the repository design including the engineered barriers, the geologic setting and its stability, how both engineered and natural barriers are expected to evolve over time, and how they are expected to provide safety
- the scientific and technical information and understanding, including the detailed support for the expected evolution and safety of the disposal system and assessments of the uncertainties in scientific understanding, models and data
- the analysis methods, computer codes and databases that are used in the modelling of the disposal system.

The adequacy and reliability of the assessment basis for carrying out safety assessments must also be addressed as a part of the safety case (Vieno & Ikonen 2005).

Finally, a synthesis will be made that draws together key findings from the safety case, namely the principal evidence, analyses and arguments that quantify and substantiate the view that the repository is safe, including an evaluation of uncertainty. This judgement is a statement of expert confidence in the safety of the disposal system in the con-text of the assessment basis available at the current stage of the repository programme (Vieno & Ikonen 2005).

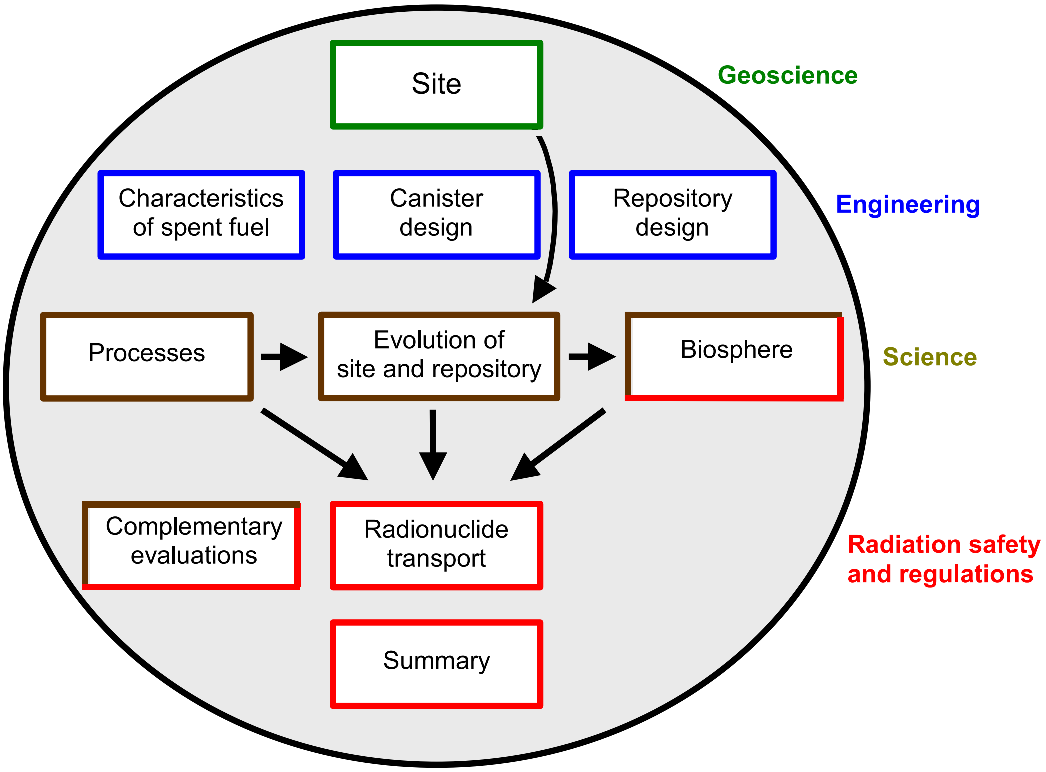


Figure 5. *Main reports of the Safety Case. The nature of the reports is indicated by the colours of the boxes. The arrows show the most important transfers of knowledge and data (Vieno & Ikonen 2005).*

1.2.2 Posiva Safety Case Portfolio

To benefit from the advantages of the long site investigation programme and close cooperation with the parallel programme of SKB, and to facilitate flexible and progressive development of the Safety Case, a portfolio approach will be employed in the reporting of the Safety Case. In practice, this implies that the main components of the Safety Case will be living, fairly independent reports based on supporting technical reports. At the various milestones of the programme (e.g. interim reporting in 2006 and 2009, and the PSAR in 2012), the reports will be linked and complemented to a Safety Case by means of additional analyses and a summary report (Vieno & Ikonen 2005).

The Safety Case portfolio will be compiled of ten main reports illustrated in Figure 5. All main reports will be written in English and they will be progressively updated (Vieno & Ikonen 2005).

For practical reasons and in order to provide consistent and transparent discussions and assessments, all biosphere aspects will be dealt with in a Biosphere assessment report at the main level of Safety Case reporting, instead of distributing them among the Site, Process, Evolution and Radionuclide Transport Reports. Elaborate discussions and descriptions of modelling details will be reported as background reports in the POSIVA and Posiva working report series (Vieno & Ikonen 2005).

1.2.3 Regulatory requirement and guidance for biosphere assessment

The regulatory requirements are set forth in the Government Decision on the safety of the disposal of spent nuclear fuel (STUK 1999). Guidance to meet these requirements is given in the regulatory Guide YVL 8.4 issued by STUK (2001). The safety regulations and guidance will be updated periodically.

The regulatory guide sets the criteria for the timeframe to be assessed. It emphasises that the repository design needs to effectively prevent the release of radionuclides into the host rock for several thousand years. For the quantitative safety assessment calculations, the regulatory endpoints for a period up to *”at least several thousand years after the closure of the repository”* but *“adequately predictable with respect to assessments of human exposure”* are dose-based. After that period, the quantitative regulatory criteria are based on constraints on the release rate of long-lived radionuclides from the geosphere into the biosphere. Consequently, the license applicant does not have to present biosphere assessments for the long-term period.

The guide also identifies the potential exposure environments and pathways to be considered. The biosphere assessment in general has to be based on similar types of climate, human habits, nutritional needs and metabolisms as the current ones, but needs to take account of reasonably predictable changes in the environment, i.e. at least the land uplift and the subsequent emergence of new land areas. At least the following exposure pathways shall be considered (STUK 2001):

- use of contaminated water as household water;
- use of contaminated water for irrigation of plants and for watering animals;
- use of contaminated watercourses and relictions.

Based on these assumptions, the most exposed individuals are to be assumed to live in a self-sustaining family or small village community in the vicinity of the disposal site, where the highest radiation exposure arises through the pathways discussed above. In the environs of the community, a small lake and a shallow water well is assumed to exist. The other members of the public are defined to live at a regional lake or at a coastal site and to be exposed to the radionuclides transported in these watercourses. In the latter case, no fixed dose constraint is set, but the acceptability of the doses depends on the number of exposed people, and they shall not exceed values from one hundredth to one tenth of the constraint for the most exposed individuals (STUK 2001).

1.2.4 Biosphere assessment portfolio

Arising from the regulatory requirements and needs of the overall Safety Case (Vieno & Ikonen 2005), the biosphere assessment needs to include detailed descriptions and quantitative analyses, for the next several thousands of years, on (Ikonen 2006)

- radionuclide transport processes and pathways,
- exposure environments and cases based on the expected evolution of the site conditions and on the regulatory requirements,
- radiation doses and/or dose conversion factors converting release rates into biosphere to dose rates,
- effects on non-human biota.

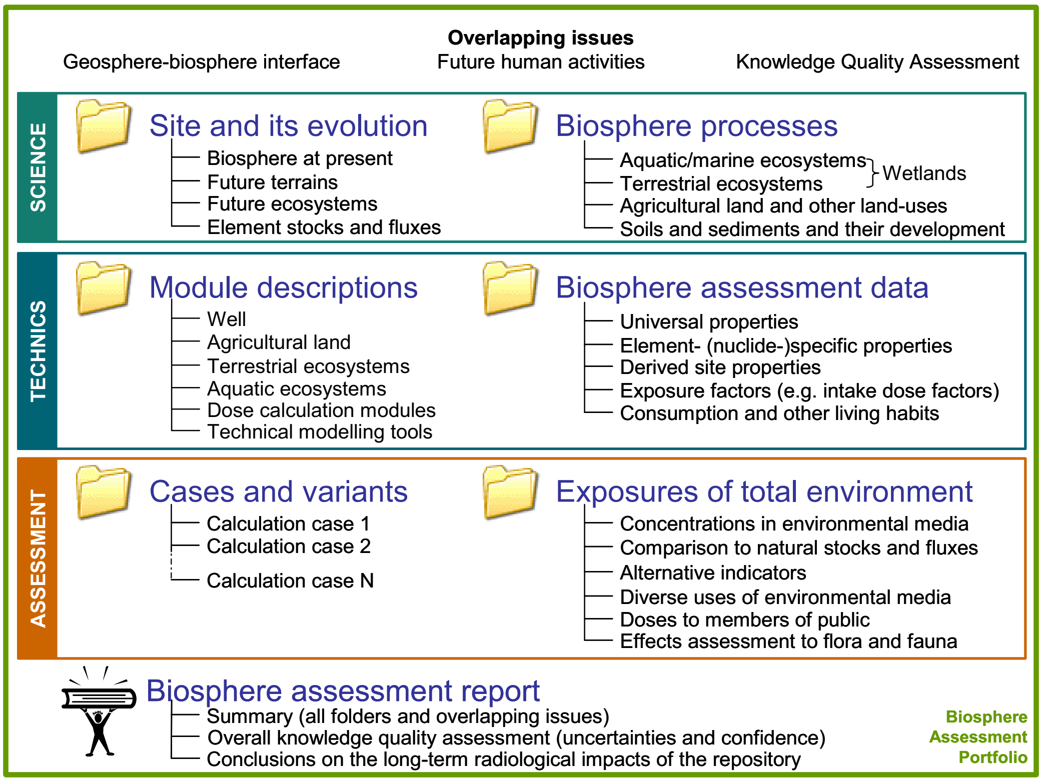


Figure 6. *Folder structure and main components of the Biosphere Assessment portfolio corresponding the current reporting plan (Ikonen 2006).*

The challenge in modern biosphere assessment is to avoid overly conservative assumptions without loosing credibility that the assessment results provide envelopes for possible exposures. This is addressed by determining probability ranges for different exposure environments and exposure types over time (especially on high land uplift rate areas such as Olkiluoto) and by assessing the dilution and accumulation processes in overburden and wells. The first aspect is especially dealt within the *terrain and ecosystems modelling* (Ikonen et al. 2007) and further in *landscape models*. Concerning the latter issue, the importance of thorough assessment of the so-called geosphere-biosphere interface and of consistency of geosphere and biosphere models regarding radionuclide flows has been recently highlighted (e.g. Egan et al. 2003).

The Biosphere Assessment Portfolio is introduced in the Safety Case planning report (Vieno & Ikonen 2005): Similar to the overall Safety Case, the biosphere assessment is divided into a number of more easily manageable components each producing one or more background reports to be summarised and integrated in the summary report ("Biosphere assessment") at the Safety Case main level (Figure 6).

1.3 Methodology

The report describes the results and conclusions from the landscape modelling case studies in 2005-2006, which represent an approach for estimating doses to inhabitants making use of a landscape which consists of several interacting ecosystems, affected by the contamination from potential radionuclide releases from a deep geological repository. The landscape and ecosystem models are implemented in the tool PANDORA (Åstrand et al. 2005). The inhabitants are assumed to spend all their lifetime in the defined landscape area, as well as to obtain all their food and water from its different ecosystems.

The input to the system is set at 1 Bq/yr for each radionuclide. The model is run over a time-span of 10000 years, and the model output is the estimated maximum and mean dose over time from the landscape to an individual. It should be noted that for all radionuclides involved in the calculations, equilibrium in the system is not reached within the scope of 10000 years.

Two types of doses are considered:

- the total dose contribution from the biosphere object that has the highest value for each point in time (DTotMax),
- the total dose contribution from the landscape, averaged over all biosphere objects (DTotMean).

From the model outputs, Landscape Dose Conversion Factors are calculated. These LDF values are similar in concept to the so-called Ecosystem-specific Dose Conversion Factors (EDF) values used for non-interacting ecosystem models (e.g. Karlsson & Bergström 2000). The LDF is calculated as

$$LDF = Total\ dose\ /\ Input \qquad (1)$$

determining the LDF unit as (Sv/yr)/(Bq/yr) = Sv/Bq. Multiplying an LDF value for a given radionuclide with a real release term yields an estimate for the dose.

Since a unit input is used in the calculations, the value of *LDFMax* is equal to the *DTotMax* value, and the *LDFMean* is equal to *DTotMean* value.

A sensitivity analysis on the outputs of the landscape models is performed using the tool EIKOS (Ekström & Broed 2006). Considering the relatively large number of parameters in the models as well as the complexity of the models themselves, as a first step a screening study of the models parameters is conducted to identify the parameters without significant influences on the model output. A full variance based uncertainty analysis is then performed for the significant parameters as identified in the screening. In addition, probabilistic simulations are performed to estimate the basic statistics of the model outputs.

1.4 Objectives of this report

The objective of the current report is to illustrate the application of the described methodology, to investigate the factors the outcome is sensitive to, and to clarify methodological aspects. The results of this analysis are intended to serve as a basis for future assessments using the same approach with reduced uncertainty both in the landscape configurations and model input data. Because of the limitations of the currently used models and input data, the derived Landscape Dose Conversion Factors are not intended to be used in actual assessments of the impacts from the planned repository. These will be addressed in future modelling using an improved data basis.

In particular, the following methodological aspects are addressed in this report:

- The impact of the landscape configurations on the resulting dose estimates is investigated in order to determine the degree of effort required in further modelling to derive reliable predictions of future landscapes.
- Important model parameters and assumptions are identified with the aim of providing guidance to the scope and priorities of site investigation programmes and to the further development and refinement of the assessment models.
- The adequacy of the databases concerning the required radionuclides is explored.
- The importance of the accumulation of radionuclides in certain landscape objects is investigated.
- The importance of different release points and their spatial distribution is investigated, determining the required level of detail and reliability of hydrogeological modelling.
- The effects of boundary conditions for the release (geosphere-biosphere interface) are analysed.

The approach to address these methodological aspects is to perform a sensitivity analysis to identify the importance of the input parameters on the predicted doses and to perform variant calculations for several calculation cases.

The current report intends to provide as many answers to the above-mentioned questions as possible. However, some issues will require further consideration applying reduced uncertainty in the landscape configurations and model input data.

The basis for the modelling and the input parameters used are described in Chapters 2 to 6. The results of these analyses are presented in Chapter 7. Conclusions are presented in Chapter 8.

2 BIOSPHERE OBJECT MODULES AND PARAMETERS

This section describes in short the sub-models used for each biosphere object and further for the different variants of the landscape. The parameter values are given in Appendix A.

Some of the biosphere object modules applied in this report have been used already in previous biosphere assessments. Following modules are adapted without changes from (Karlsson & Bergström 2000):

- Lake module;
- Coast module;
- Wetland module.

The other modules used in the current report are described in the following sections.

2.1 Forest module

The forest module used in the landscape models in this report is identical to the model described in (Avila 2006a) with the exception that a constraint to the calculation of the runoff was added. This was necessary because some combinations of the precipitation rate, the intercepted fraction and the transpiration lead to a negative value of the runoff during the probabilistic simulations. The cause of this is that the probability density functions for the above mentioned parameters are derived using measurement data from many different locations. Thus, one remedy to this would be to only use measurement data for the Olkiluoto region in future work. In the current report, however, this was not possible and, therefore, a lower constraint of zero is applied for the calculated runoff.

2.2 Running water module

The running water module used in the landscape models in this report is implemented from (Jonsson & Elert 2005). However, one conclusion of the use of this particular model in the current report was that the parameterisation assumed a high knowledge of the site-specific characteristics and properties for the identified running water objects in the landscape models developed. This is not only due to the fact that future landscape scenarios are considered, where data has to be estimated or extrapolated based on current knowledge, but also due to the higher complexity of the model compared to the rest of the ecosystem models used. Since this modelling work was done, a new report has been published (Jonsson & Elert 2006), addressing some of the issues mentioned here, and the model version described in this report preferably should be used in future landscape modelling.

2.3 Implementation in PANDORA

The biosphere object modules were implemented in PANDORA (Åstrand et al. 2005) one by one, and then saved into a common library file. When the individual landscape models were developed, each instance of a biosphere object was copied from this library file, reducing the risk of using wrong versions of the modules. Another benefit of using biosphere object modules from a library file is that in the case that one needs to perform a modification to module, this change only needs to be done on the module in the library, and it is then automatically updated in all places where it has been used.

3 LANDSCAPE MODELS AND PARAMETERS

This section describes four different landscape configurations that were studied. The configurations correspond to future time periods, starting from the present conditions and covering a period of approximately 6000 years.

The terrain development modelling was carried out by Ari Ikonen (Posiva) and the landscape model configuration developed by him and the author, Robert Broed (Facilia). The geometrical properties and catchment areas were then determined from the terrain development model by Ari Ikonen, and for forest vegetation types data from (Rautio et al. 2005) was utilised.

3.1 Derivation of landscape models and parameters

For outlining the biosphere objects and calculating their geometrical properties, four temporal snapshots on the terrain development were developed from bathymetrical data to represent the main phases in the development of the area. Snapshot times were selected to represent the major changes in the terrain (mainly separation of lake basins from the sea) and further adjusted to converge with convenient elevation/depth contours.

Similar to an earlier study (Rautio et al. 2005), the elevation of the study area was estimated after a uniform land uplift using the depth data from nautical maps and (Rantataro 2001). The apparent land uplift was calculated from the site-specific isostatic crust uplift and eustatic sea level equations given in (Löfman 1999, p. 40-41). Locations and areas of future lakes were estimated to follow the topographical depressions under the sea level, decreased by an area along the shore filled in by sedimentation and vegetation. The location of the rivers was estimated by following the path of lowest elevations, usually characterised also by accumulation of clayish sea bottom sediments. Wetlands were allocated to depressions where sedimentation occurring at present according to data of (Rantataro 2001).

In the present case study, some depth and stratigraphy profiles were drawn from the data of (Rantataro 2001) over the model area for better estimation of the largest extent of lakes. By comparing the profiles intersecting the lakes, thresholds for the water levels were estimated and the approximate circumference of each lake was manually digitised on basis of the depth contours and more detailed pointwise depth data of (Rantataro 2001).

For areas currently above sea level, the future vegetation types were estimated on the basis of the types at present. The vegetation types for the new land areas emerging with the land uplift were then forecasted on basis of deduction rules (Rautio et al. 2005). The vegetation types at present will prevail also on the new land areas in the future because the emerging sea bottom resembles the present soil, taking into account the soil formation processes. The rules were left rather simple and partly subjective to the authors, such as

- newly emerged or large rock outcrops: rock forest,

- older outcrops and areas on water dividers: pine forest,
- intermediate areas: spruce forest,
- river banks: deciduous forest,
- in the middle of coniferous and deciduous areas: mixed forest, and
- perimeter of lakes: outwards in the order wetland, deciduous, mixed, pine forest.

The landscape or object specific parameters of the landscape models are listed in Appendix A with their values applied.

3.2 Description of the landscape model stages

The landscape of 0 AP (the present; Figure 7) is characterized by two bays, north and south of the Olkiluoto area. On the northern side, the Eurajoki River has its outflow, and on the eastern side the Lapinjoki River, with a substantially smaller annual flow rate compared to Eurajoki. The runoff from the northern forest flows directly to the northern inner coast. The runoff from the southern forest flows directly to the nearest inner coast (Inner Coast 2).

The landscape of first larger lakes (approximately 1450 AP; Figure 8) corresponds to land uplift of ca. 9 meters (evenly distributed uplift rate). The northern bay becomes more like a lake. In the area east of the bay several lakes and connecting rivers are emerging. The runoff from the northern forest is equally divided between the two lakes (Kornanjärvi and Kiskarinjärvi). The southern bay has become totally isolated and forms a large lake (Liponjärvi). Also a couple of wetlands and a smaller lake have emerged.

The landscape of young inland site (approximately 1985 AP; Figure 9) corresponds to land uplift of ca. 10 meters (evenly distributed uplift rate). The northern bay has now become isolated and forms a lake (Susijärvi) which is connected to the coast through a river (Pitkäjoki). The runoff from the northern forest is equally divided between the two lakes (Kornanjärvi and Kiskarinjärvi). Along the coastline several smaller bays are forming with rather limited water-exchange with the sea. The two northernmost inner coast objects (Inner Coast 1 and 2) have a direct water exchange between each other. The large lake in the southern region decreases in area because of sedimentation processes.

The landscape of far future (approximately 5850 AP; Figure 10) corresponds to land uplift of ca. 25 meters (evenly distributed uplift rate). All the inner coast objects have become wetlands and rivers. The runoff from the northern forest is equally divided between the two lakes (Kornanjärvi and Kiskarinjärvi). The Pitkäjoki River is now considerably longer and discharges directly to the outer coast region. In the southern region, a wetland and two rivers have formed, connecting the Liponsuo wetland with the outer coast.

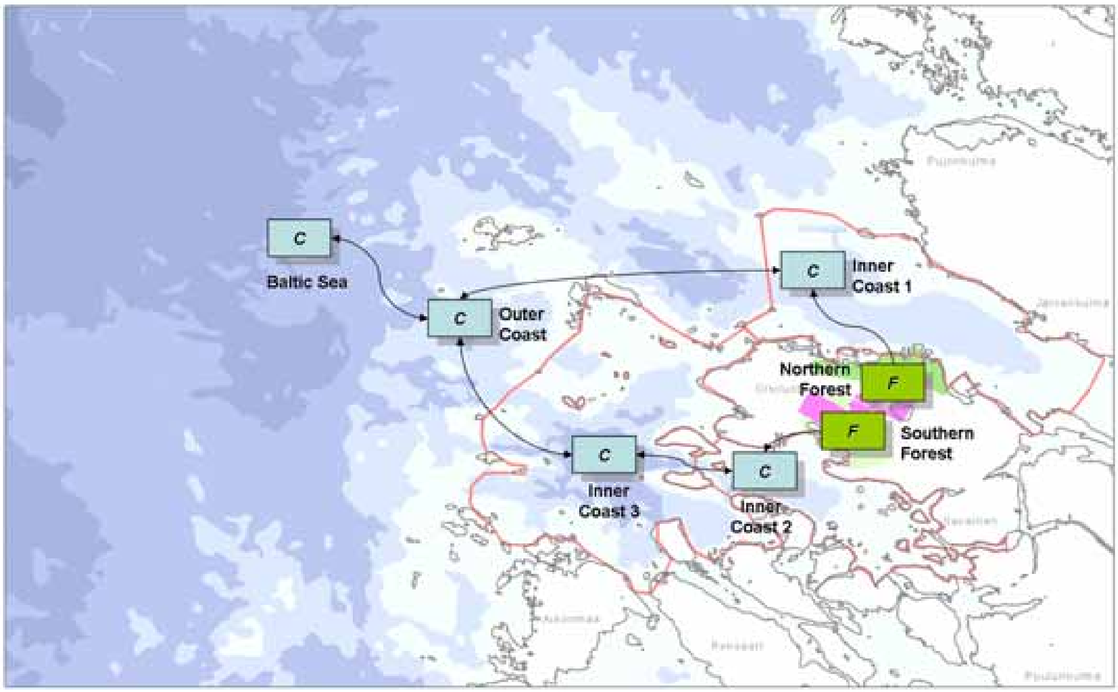


Figure 7. *The landscape of 0 AP (the present)*

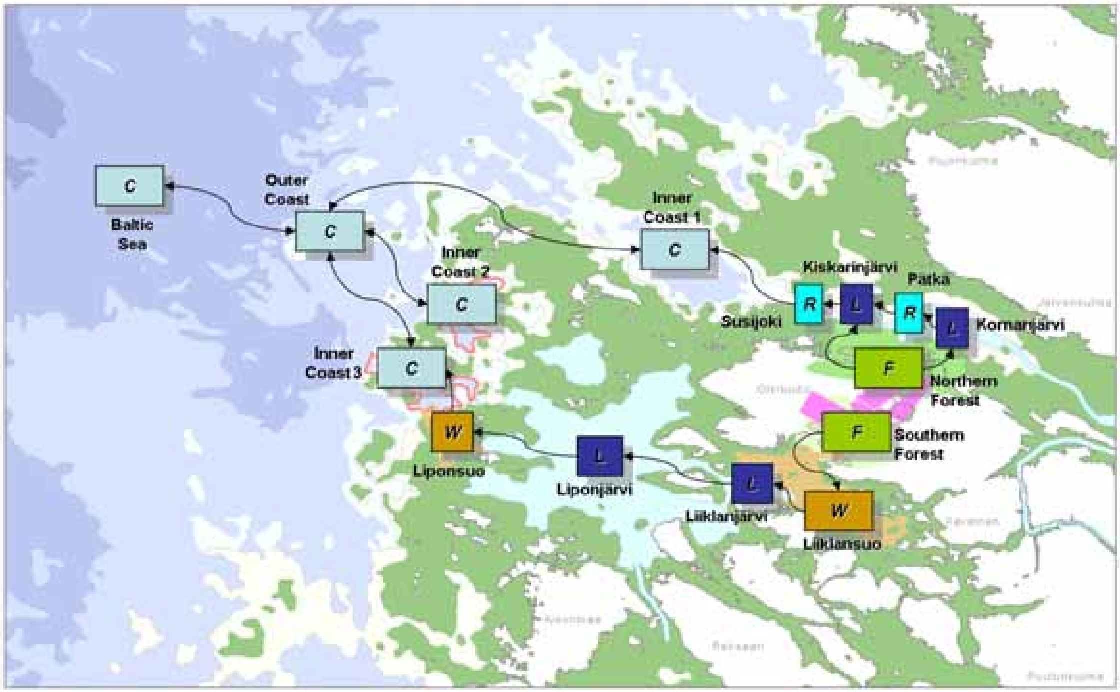


Figure 8. *The landscape of first larger lakes (approximately 1450 AP)*

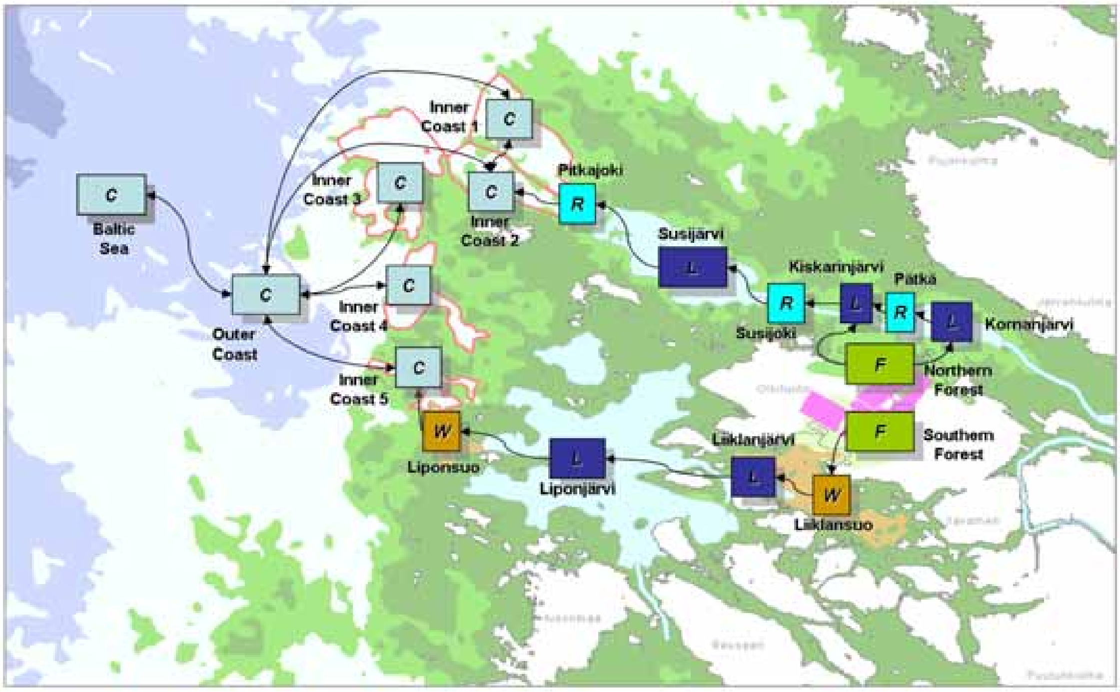


Figure 9. The landscape of young inland site (approximately 1985 AP)

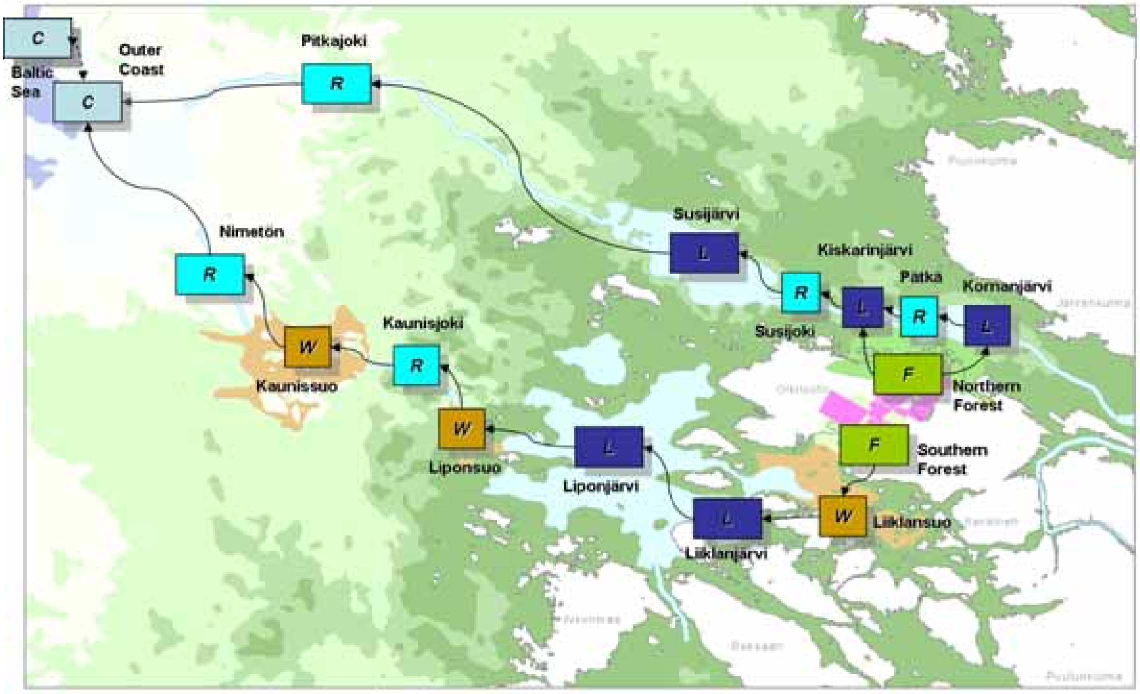


Figure 10. The landscape of far future (approximately 5850 AP)

4 SOURCE TERMS AND DOSE ESTIMATION METHOD

This section describes the release scenarios considered and the methods used for estimating the doses for each biosphere object and for each landscape configuration.

4.1 Radionuclides included

Included in the simulations in this exercise are radionuclides which, based on the previous assessments (SKB 1999, 2004; Vieno & Nordman 1999), are expected to give the highest dose contributions, Ni-59, Se-79, I-129 and Ra-226. Some further radionuclides (Cl-36, Tc-99, Cs-135, Pu-239 and Am-241) with contrasting properties and environmental behaviour are also considered. The two short-lived radionuclides Pb-210 and Po-210 were included in the Ra-226 decay chain to study the effects of decay chains to the total dose. It should be noted that C-14, which is also a potentially important radionuclide, was not included in the study. The reason for excluding C-14 was that the applied models are not directly applicable to this radionuclide. The required upgrading of the models is currently ongoing by utilising the information gained in the site investigation program about carbon cycling, which will allow the inclusion of C-14 in future assessments. In Table 1, the included radionuclides are listed.

Table 1. *Radionuclides included in the simulations.*

Radionuclide	Halflife [years]
Cl-36	3.010E+05
Tc-99	2.110E+05
I-129	1.570E+07
Ni-59	7.600E+04
Pu-239	2.411E+04
Cs-135	2.300E+06
Se-79	1.130E+06
Am-241	4.322E+02
Th-230	7.538E+04
Ra-226	1.600E+03
Pb-210	2.230E+01
Po-210	4.000E-01

4.2 Source term

For each landscape configuration, the source rate is defined as 1 Bq/yr to the system for each included radionuclide. As an exception to this, for the short-lived daughter nuclides of Ra-226 (including Po-210 and Pb-210) only ingrowth from the parent nuclide is considered.

The total release is distributed over the biosphere objects in each landscape configuration, at fractions estimated from the density of observed fracturing along the bedrock lineaments (Kuivamäki 2005) close to each object as given in Table 2.

Table 2. *Release fractions applied in the landscape models.*

Object	Present	First lakes	Young inland	Far future
Forest North	2.1E-01	2.1E-01	2.0E-01	2.0E-01
Forest South	7.1E-02	7.0E-02	6.6E-02	7.0E-02
Inner Coast 1	1.4E-01	4.9E-02	2.1E-02	–
Inner Coast 2	3.6E-01	–	4.1E-02	–
Inner Coast 3	2.1E-01	–	–	–
Inner Coast 4	–	–	–	–
Inner Coast 5	–	–	–	–
Baltic Sea	–	–	–	–
Kiskarinjärvi	–	3.5E-02	3.2E-02	3.0E-02
Kornanjärvi	–	2.1E-01	2.0E-01	2.0E-01
Liiklanjärvi	–	2.8E-02	2.7E-02	3.0E-02
Liiklansuo	–	1.1E-01	1.1E-01	1.1E-01
Liponjärvi	–	2.9E-01	2.7E-01	2.7E-01
Susijoki	–	7.0E-04	6.6E-02	6.6E-04
Susijärvi	–	–	2.0E-01	7.0E-02
Kaunissuo	–	–	–	1.0E-02
Nimetön	–	–	–	6.6E-04
Pitkäjoki	–	–	–	2.0E-01

4.3 Calculation of dose estimates to each biosphere object

The doses from the different biosphere objects were calculated according to (Avila et al. 2006). Only a brief overview of the dose calculations is given here.

To facilitate calculations of doses from ingestion of food produced in different biosphere objects, aggregated transfer factors were derived for each ecosystem type. In the dose calculations for SR-Can (Avila et al. 2006; Avila & Bergström 2006), it was assumed that the exposed individuals get the whole yearly demand of carbon (a value of 110 kg C/yr (Avila & Bergström 2006) was used) from the ecosystem considered.

From the simulations with the models, activity concentrations in water and soil were obtained. These were then multiplied by the aggregated transfer factors (Avila et al. 2006) to obtain concentrations in food products (in Bq/kg_C). Effective dose rates (in Sv/a) per unit release rate (in Bq/a) to an adult individual were calculated using the methods described in (Avila & Bergström 2006).

In this report, the term ‘dose’ refers to ‘effective dose’ which is the sum of the effective dose due to external exposure and the committed effective dose due to internal exposure. For terrestrial ecosystems, internal doses from inhalation and food ingestion as well as external doses were considered in the calculations. For aquatic ecosystems, only doses from the ingestion of water (for lakes and rivers) and food (for sea, lakes and rivers) were considered, since previous assessments (SKB 1999, 2004; Vieno & Nordman 1999) have shown that in these types of ecosystems other exposure pathways give a very low contribution to the total doses. In the case of food ingestion doses, a correction factor ($CorrD_{eco}$) was introduced for cases in which the size of the food production in the ecosystem is not sufficient to support a single person with food:

$$CorrD_{eco} = \min(1, N_{eco}) \tag{2}$$

$$N_{eco} = \frac{pty_{eco} * Area_{eco}}{IR_C} \tag{3}$$

where

N_{eco} is the number of individual that can be supported by the ecosystem [-],

pty_{eco} is the productivity of the different ecosystem types [$kg_C/m^2/a$],

$Area_{eco}$ is the area of the ecosystem [m^2],

IR_C is the yearly intake of carbon by an individual [kg_C/a],

and *eco* denotes the ecosystem object in question..

In Table 3, a summary of the calculations used in estimating the doses from the biosphere objects are presented.

4.4 Calculation of landscape doses

The two types of dose values calculated were: the maximum of the total dose from all biosphere objects and the mean overall total dose contributions from all biosphere objects. In Table 4 the equations used are summarised.

4.5 Implementation in PANDORA

To facilitate the calculation of doses from the landscape, generic blocks were implemented in PANDORA (Åstrand et al. 2005). For the biosphere objects, two blocks were created: one for calculating the activity concentrations in different media and in food, and another for calculating the dose contribution for the ecosystem-specific pathways.

On the landscape level, blocks were implemented for calculating the maximum and mean of the total dose from all biosphere objects.

The blocks were created in a generic way so that only one type of block is required independent of which type of biosphere object it is placed in, and what number of biosphere objects is used in a model. In other words, these blocks can be used in any landscape configuration in the same way and will automatically provide the correct dose values from the landscape. In figures 11-12, these blocks are illustrated.

Table 3. *Equations used in calculating the activity concentrations in different media and food from the biosphere objects.*

Object type	**Cair** [Bq/m^3] (concentration of radionuclides in air)	**CsoilVol** [Bq/kg_{dw}] (concentration of radionuclides in soil)	**CFreshWaterMean** [Bq/m^3] (concentration of radion. in drinking water)	**Cdiet** [Bq/kg_C] (concentration of radionuclides in the diet)
Forest	Csoil*DustConc	Csoil*DensitySoilBulk		Csoil*CRforest
Mire	Csoil*DustConc	Csoil*DensitySoilBulk		Csoil*CRforest
Lake			Mean(ConcFreshWater)	ConcFreshWater*BFlake
River			Mean(ConcFreshWater)	ConcFreshWater*BFlake
Coast				ConcSea*BFcoast

Table 4. *Equations used in calculating doses from biosphere objects.*

Object type	**Dext** [Sv/y] (dose from external exposure)	**Dinh** [Sv/y] (dose via inhalation)	**Dingwat** [Sv/y] (dose via ingestion of water)	**Ding** [Sv/y] (dose via ing. of food)	**N** (no. of individuals supported by the object)	**DTotal** [Sv/y] (total dose to an individual)
Forest	CsoilVol* ExposureTime*DCCext	Cair* ExposureTime* InhalationRate*DCCinh	Cdiet*IRcarbon*DCCing	Area*pty_forest/ IRcarbon	Dext+Dinh+ Min(1,N)*Ding	Dext+Dinh+ Min(1,N)*Ding
Mire	CsoilVol *ExposureTime*DCCext	Cair* ExposureTime* InhalationRate*DCCinh	Cdiet*IRcarbon*DCCing	Area*pty_mire/ IRcarbon	Dext+Dinh+ Min(1,N)*Ding	Dext+Dinh+ Min(1,N)*Ding
Lake			ConcFreshWater* IRwater*DCCing	Cdiet*IRcarbon* DCCing	Area*pty_lake/ IRcarbon	Dingwat+ Min(1,N)*Ding
River			ConcFreshWater* IRwater*DCCing	Cdiet*IRcarbon* DCCing	Area*pty_runwat/ IRcarbon	Dingwat+ Min(1,N)*Ding
Coast				Cdiet*IRcarbon* DCCing	Area*pty_coast/ IRcarbon	Min(1,N)*Ding

Table 8. *Equations used in calculating landscape doses. SD(*x*) denotes the standard deviation of* x *and SQRT(*x*) the square root of* x.

Abbreviation	**Meaning**	**Equation** (cf. Table 7)	**Included objects from the landscape**
DextMean	Mean landscape dose from external exposure	Mean(Dext)	All terrestrial objects that exist
DinhMean	Mean landscape dose from inhalation	Mean(Dinh)	All terrestrial objects that exist
DingwatMean	Mean landscape dose from ingestion of water	Mean(Dingwat)	All freshwater objects that exist
DingMean	Mean landscape dose from ingestion of food	1/Ntotal*Sum(N*Ding)	All objects that exist
Ntotal	Total number of individuals supported by the landscape	Sum(N)	All objects that exist
DTotalMean	Mean landscape dose (all exposure types)	DextMean+DinhMean+DingwatMean+DingMean	
DextSD	Standard deviation of doses from external exposure	SD(Dext)	All terrestrial objects that exist
DinhSD	Standard deviation of doses from inhalation	SD(Dinh)	All terrestrial objects that exist
DingwatSD	Standard deviation of doses from ingestion of water	SD(Dingwat)	All freshwater objects that exist
DingSD	Standard deviation of doses from ingestion of food	SQRT(1/Ntotal*Sum(N*(Ding-DingMean)^2))	All objects that exist
DTotalSD	Standard deviation of landscape doses (from all exp. types)	SQRT(DextSD^2+DinhSD^2+DingwatSD^2+DingSD^2)	
DTotalMax	Maximum landscape dose (all exposure types)	Max(Dtotal)	

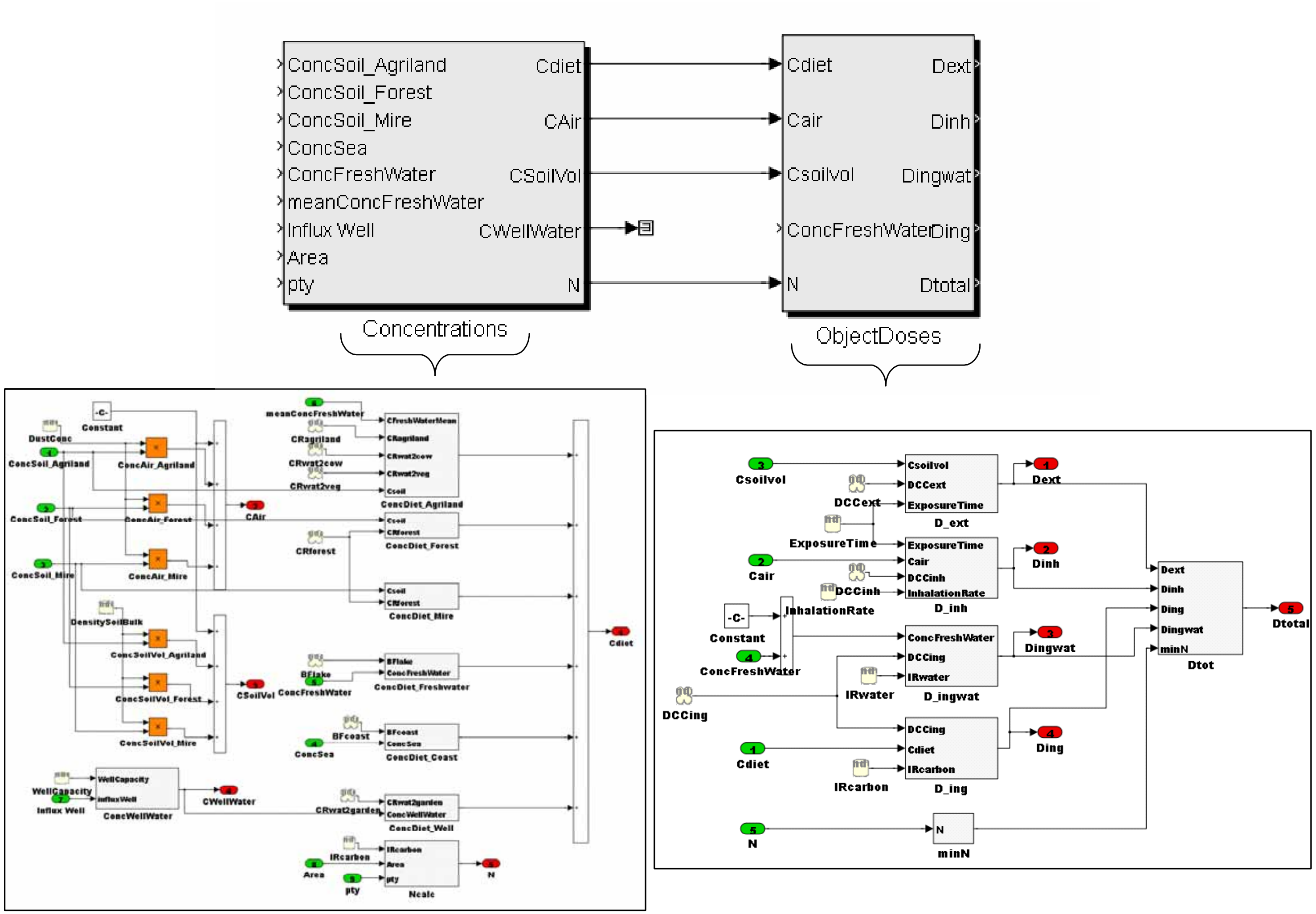


Figure 11. Illustration of the biosphere object dose blocks implemented in PANDORA.

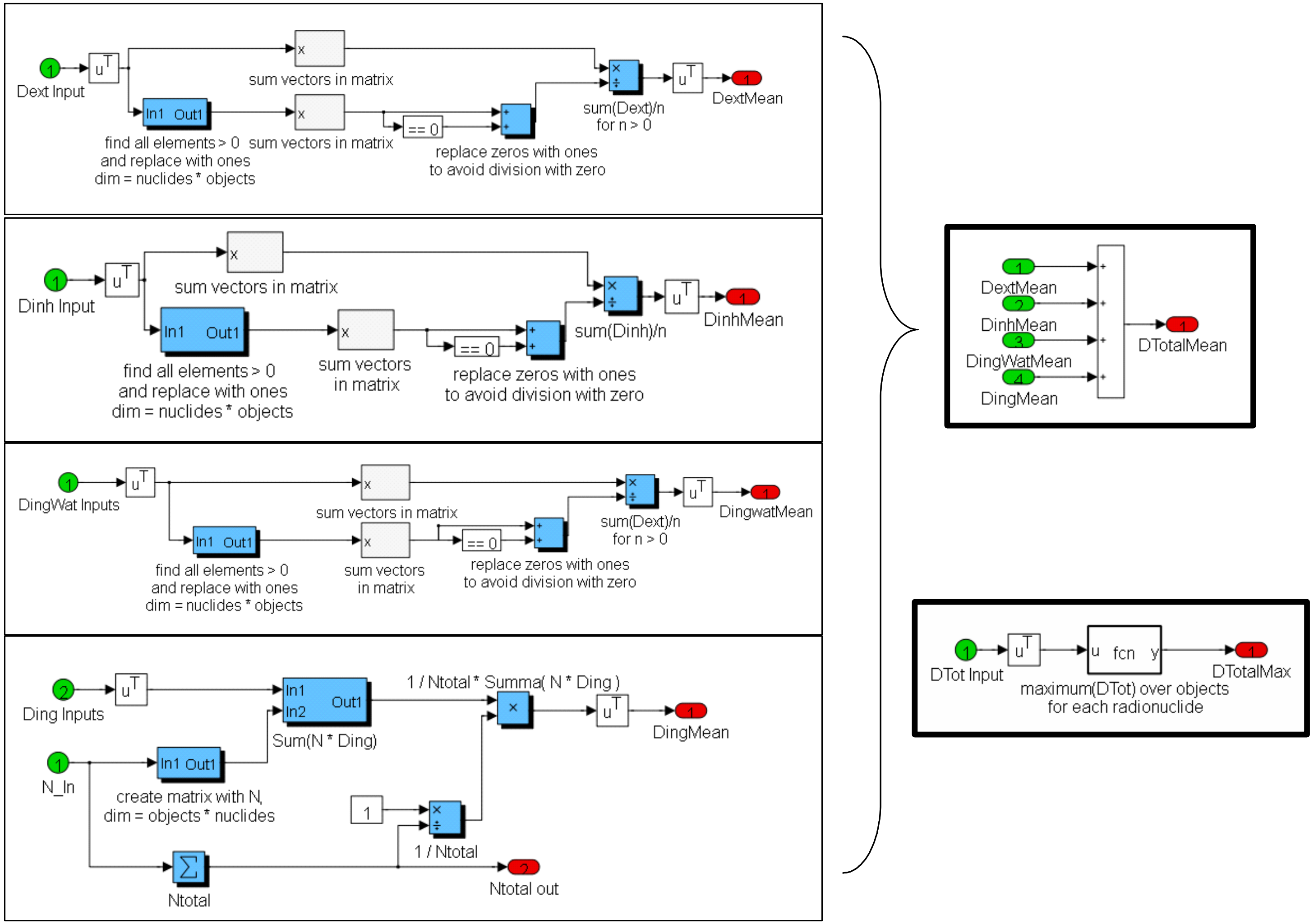


Figure 12. *Illustration of the PANDORA blocks for calculating the landscape doses.*

5 METHODS FOR SENSITIVITY ANALYSIS

In this chapter, methods used for the sensitivity analyses are described. For more detailed description of the methods, see (Ekström & Broed 2006).

5.1 Screening methods

For models containing large amounts of input parameters with inherent uncertainties, screening methods can be used to identify those parameters which have the strongest effect on the output variability by performing only a few model runs. This reduces the number of input parameters to be examined in a detailed sensitivity analysis. Using this approach, it is often found that the number of significant input parameters is quite small compared to the total number of input parameters in a model.

The most appealing property of the screening methods is their low computational costs, i.e. the required number of model runs. A drawback of the screening approach is that the sensitivity measure is only qualitative in the sense that the input parameters are ranked in the order of significance, but that their absolute contribution is not quantified.

In the assessment, two different screening methods are applied: the method of Garten and the method of Morris (Ekström & Broed 2006). In this case, the approach selected is to use both methods, and to identify the parameters indicated by either method as significant. The idea was to study the agreement of the results of the two methods and also to see how well the methods compared.

As for selecting criteria for the screening, no general rule exists and these have to be chosen with some degree of arbitrariness. The measure used for this criterion is that those parameters are identified having a relative effect equal to or larger than 1% compared to the total effects normalized over all parameters.

5.1.1 Garten's method

The method of Garten is a relatively simple screening method, requiring only a minimum and a maximum value for a given input parameter. The sensitivity index is calculated as:

$$1 - \min(\mathrm{Y}(Xi)) / \max(\mathrm{Y}(Xi)) \qquad (6\text{-}1)$$

where $\mathrm{Y}(Xi)$ is the model output when varying the input parameter Xi and keeping all other input factors fixed at nominal values. The method is not able to recognize possible non-linearities between the input parameters and the model outputs, and no interactions between input parameters. A benefit of the method is that it requires very low number of model simulations, and is easy to interpret.

5.1.2 Morris' method

The method of Morris computes elementary effects for all input parameters. Mean and standard deviation of these elementary effects gives qualitative results of the parameter impact of the output variability. The method of Morris is a screening method, thus it does not require as many realisations of the model to compute reliable results as a quantitative method. With the Morris method the input uncertainty is either described using a maximum and a minimum value or using probability distributions.

The Morris method is global in the sense that it varies over the whole range of uncertainty of the input factors. It can also determine if the effect is 1) negligible, 2) linear and additive, 3) non-linear, and 4) involved in interactions with other input factors.

5.2 Variance-based method (Sobol)

This method computes first order sensitivity index (SI) and total order sensitivity index (TSI). Using SI and TSI quantitative results of the parameter impact to the output variance regardless of the input/output relationship are obtained. Parameter uncertainty is described using probability distributions. This method requires that the input parameters are uncorrelated, thus there is no way to induce a correlation structure onto the sample set. However, for these test cases no correlations were defined between the parameters. The sensitivity indexes are calculated as in equations (6-2) and (6-3): Equation (6-2) gives the expected amount of variance that would be removed from the total output variance, if we were able to learn the true value of parameter Xi, divided by the total unconditional variance. Equation (6-3) is the expected amount of output variance that would remain unexplained if parameter Xi, and only Xi, were left free to vary, and all other parameters having been learnt, divided by the total unconditional variance ($X{\sim}i$ are all the input parameters except Xi).

$$\mathrm{SI} = \mathrm{V}[\mathrm{E}(\mathrm{Y}|Xi)]/\mathrm{V}(\mathrm{Y}) \qquad (6\text{-}2)$$

$$\mathrm{TSI} = \mathrm{E}[\mathrm{V}(\mathrm{Y}|X{\sim}i)]/\mathrm{V}(\mathrm{Y}) \qquad (6\text{-}3)$$

The Sobol method provides quantitative measures of the parameter impacts, but also require relatively large number of model simulations. The number of simulations are $N(2k+1)$, where N is the number of samples, and k is the number if input factors (i.e. model parameters included in the sensitivity analysis run).

6 RESULTS AND DISCUSSION

Section 6.1 describes the modelling results for the central calculation case, i.e. constant 1 Bq/y source term for each nuclide and nominal values for the parameters, for the four landscape configurations. As indicated in Section 1.4, these are to be seen only as first estimates. Current uncertainties of the modelling results are analysed in Section 6.2 using a probabilistic approach based on the estimates for parameter uncertainties provided in the appendices.

A main objective of the current report is to identify the relative importance of the different input parameters for the dose assessments. For this purpose, sensitivity analyses are conducted. Their results are presented in Section 6.3.

A further objective is to address specific issues as described in Section 1.4. This requires carrying out some variant calculations which are presented and discussed in Section 6.4.

6.1 Central case

The results for the central parameter values (nominal values) are presented in the following figures 13…24 for the present landscape and for the predicted landscapes of the first larger lakes, the young inland site and the far future. For each landscape configuration, the following results are shown:

- the maximum of the total dose for each radionuclide as a function of time (fig. 13, 16, 19, 22);
- the fractions of the total doses for each object in the landscape model at the time when the maximum value occurred (fig. 14, 17, 20, 23);
- the fraction of the total release retained in the system over time, with losses occurring to the Baltic Sea as well as due to radioactive decay (fig. 15, 18, 21, 24).

Discussion

Notwithstanding the restrictions of the current modelling, some conclusions already can be drawn from the results presented in the preceding sections. It is believed that these conclusions in principle will remain valid for the future improved models. Nevertheless, this will require to be further studied. In particular, it should be investigated what effect a dynamic change of the landscape as opposed to the static consideration in this report has on the following conclusions.

On the basis of the results shown in figures (13-24), it can be concluded that:

- The variation of the landscape dose conversion factors between the different landscape configurations amounts to less than an order of magnitude. Based on current modelling, it is expected that this result will be confirmed by future modelling with an improved data basis. The important conclusion to be drawn from this result is that assumptions of future landscape development will not affect the predicted doses to a larger extent than one order of magnitude at most. This finding is important for the building of confidence into the safety

Present landscape

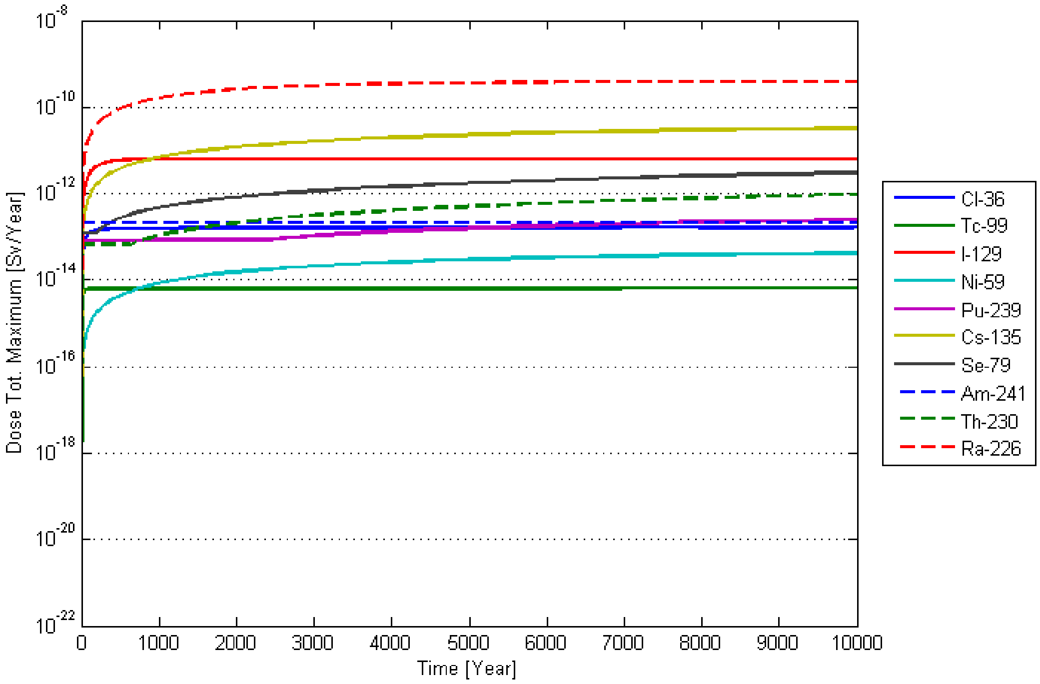


Figure 13. *The maximum of the total dose for each radionuclide as a function of time. The results are for the central case of the present landscape. For Ra-226, the value is the sum of the dose-contributions from Ra-226 and its two daughter nuclides Pb-210 and Po-210.*

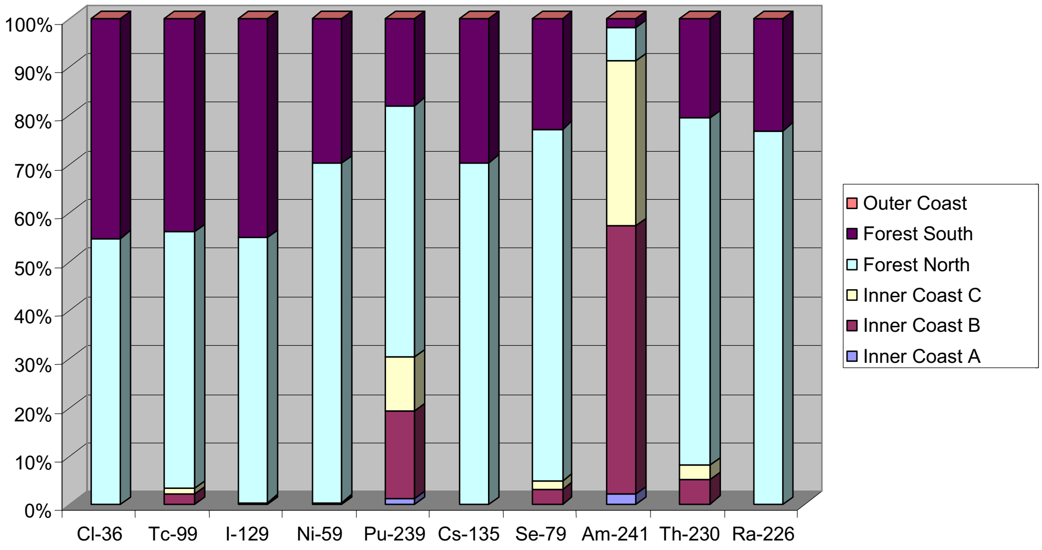


Figure 14. *Fractions of the total doses for each object in the landscape model of the present at the time when the maximum value occurred. The value for Ra-226 contains the contributions from its daughter nuclides Pb-210 and Po-210.*

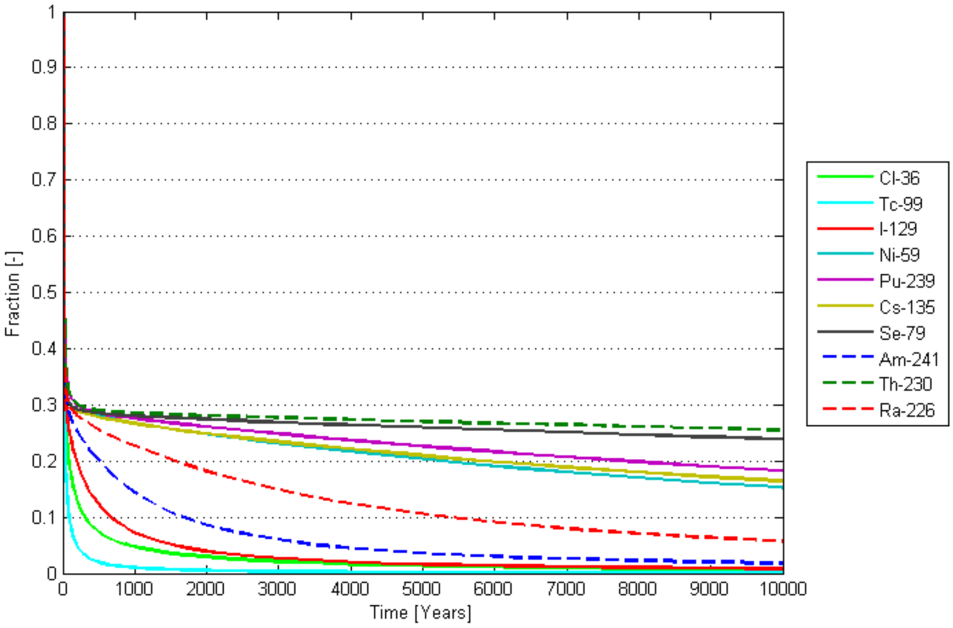


Figure 15. *Fraction of total release retained in system of the present landscape over time. The loss from the system is the amount in the Baltic Sea and the dilution from it, as well as the loss due to radioactive decay.*

Landscape of first larger lakes

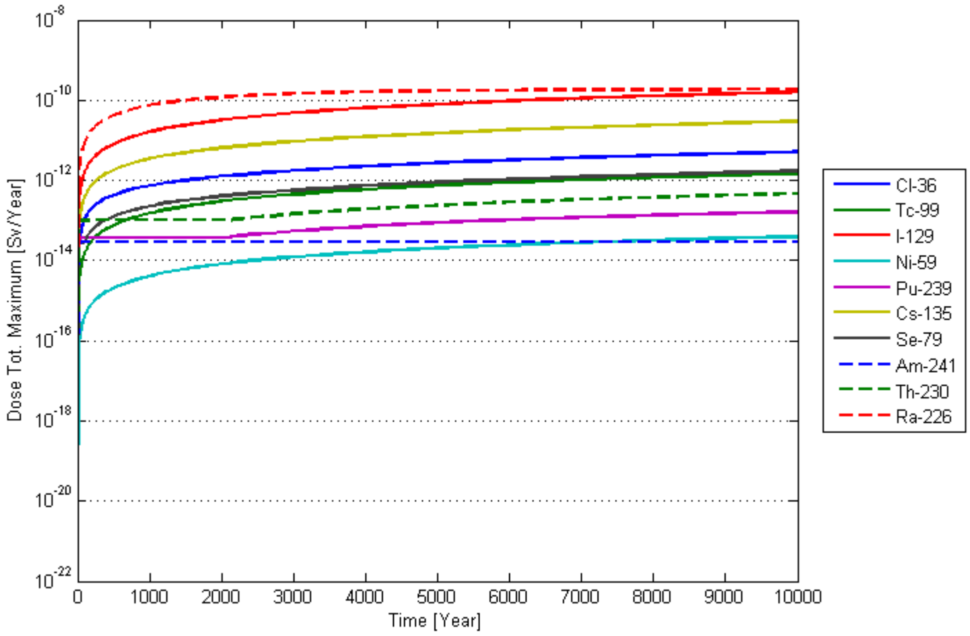


Figure 16. *The maximum of the total dose for each radionuclide as a function of time. The results are for the central case of the landscape of first larger lakes. For Ra-226, the value is the sum of the dose-contributions from Ra-226 and its two daughter nuclides Pb-210 and Po-210.*

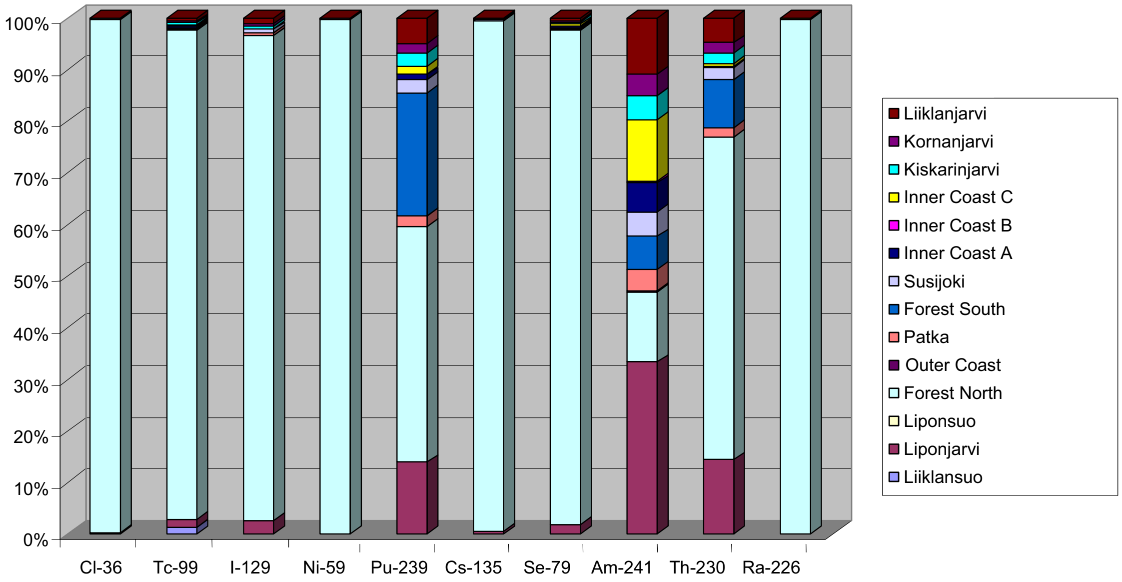


Figure 17. *Fractions of the total doses for each object in the landscape model of first larger lakes at the time when the maximum value occurred. The value for Ra-226 contains the contributions from its daughter nuclides Pb-210 and Po-210.*

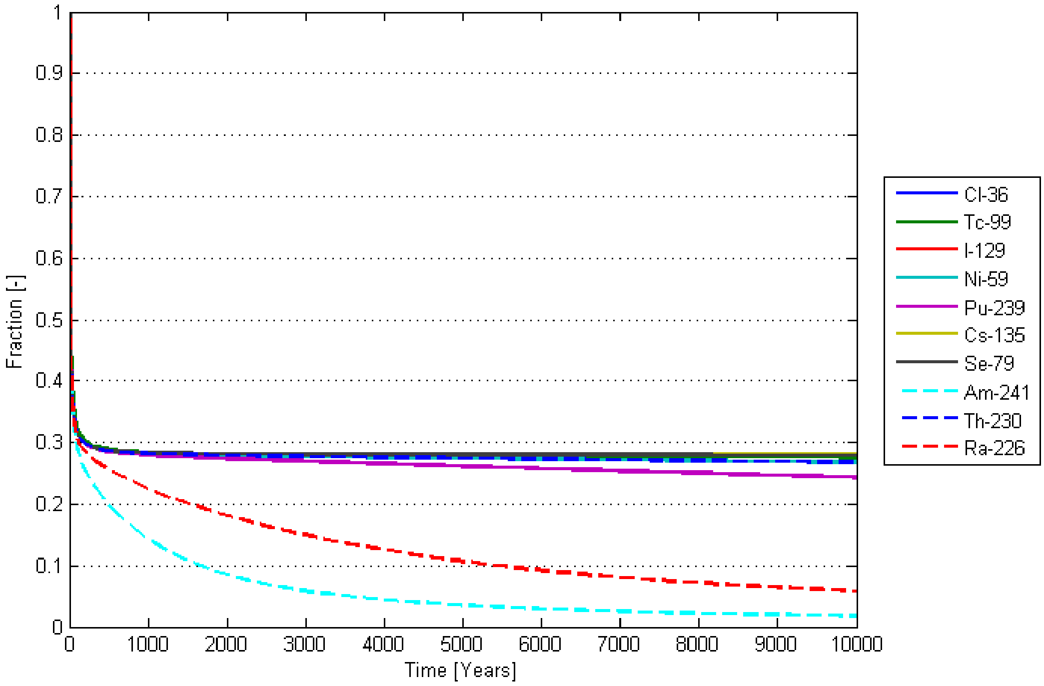


Figure 18. *Fraction of total release retained in system of the first larger lakes over time. The loss from the system is the amount in the Baltic Sea and the dilution from it, as well as the loss due to radioactive decay.*

Landscape of young inland site

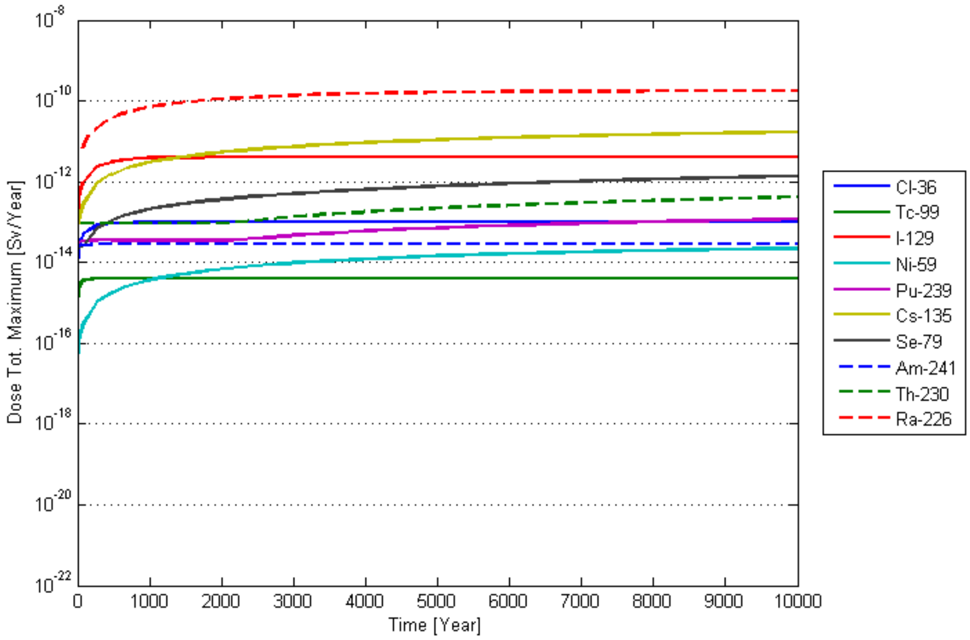


Figure 19. *The maximum of the total dose for each radionuclide as a function of time. The results are for the central case of the landscape of young inland site. For Ra-226, the value is the sum of the dose-contributions from Ra-226 and its two daughter nuclides Pb-210 and Po-210.*

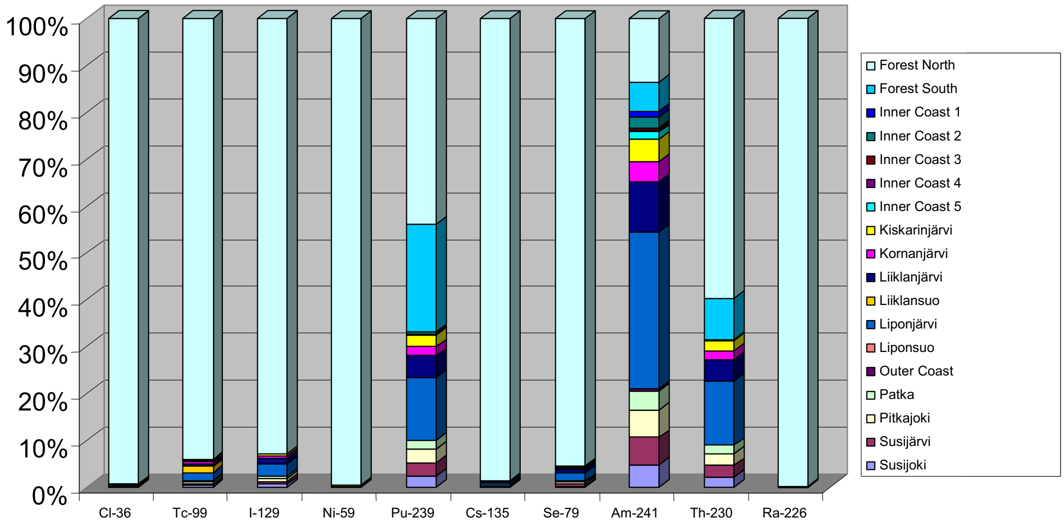


Figure 20. *Fractions of the total doses for each object in the landscape model of young inland site at the time when the maximum value occurred. The value for Ra-226 contains the contributions from its daughter nuclides Pb-210 and Po-210.*

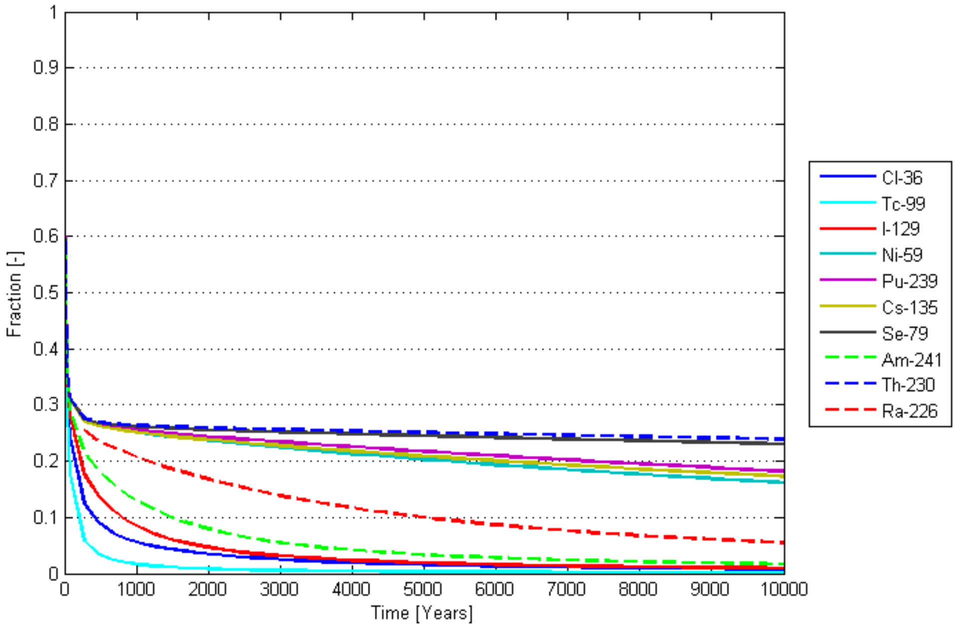


Figure 21. *Fraction of total release retained in system of the young inland site over time. The loss from the system is the amount in the Baltic Sea and the dilution from it, as well as the loss due to radioactive decay.*

Landscape of far future

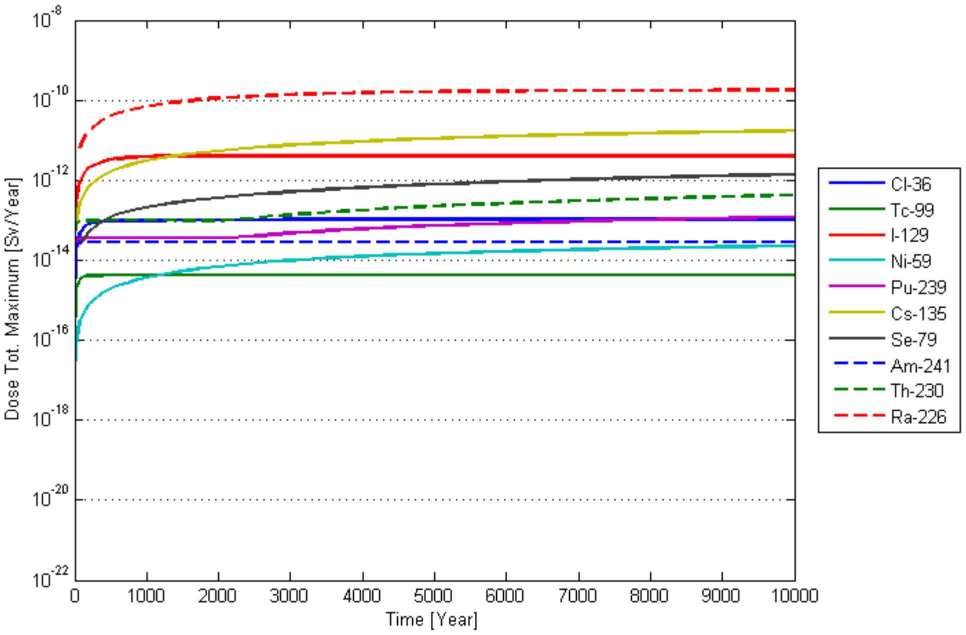


Figure 22. *The maximum of the total dose for each radionuclide as a function of time. The results are for the central case of the landscape of far future. For Ra-226, the value is the sum of the dose-contributions from Ra-226 and its two daughter nuclides Pb-210 and Po-210.*

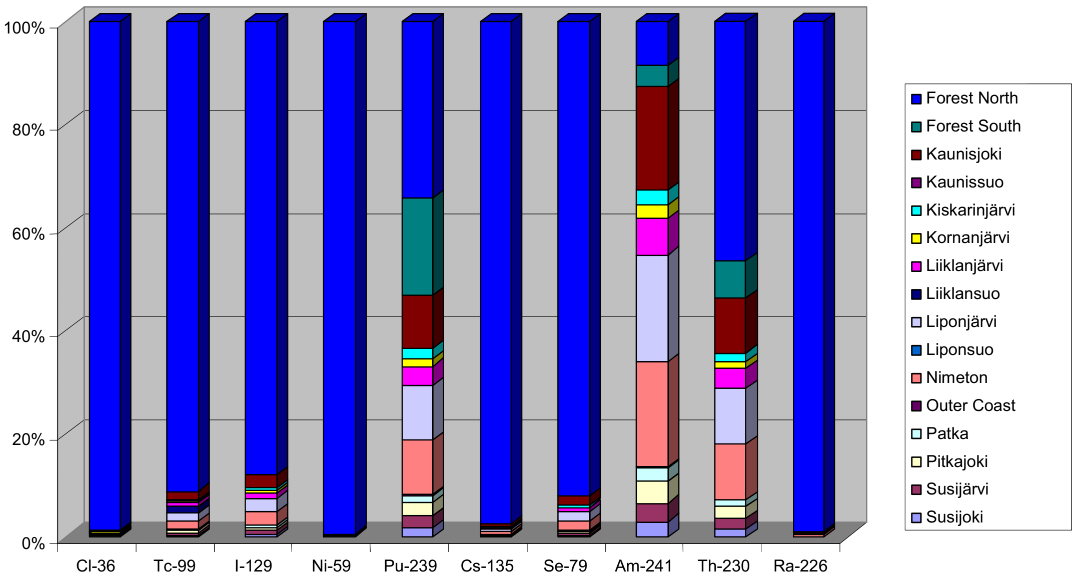


Figure 23. *Fractions of the total doses for each object in the landscape model of far future at the time when the maximum value occurred. The value for Ra-226 contains the contributions from its daughter nuclides Pb-210 and Po-210.*

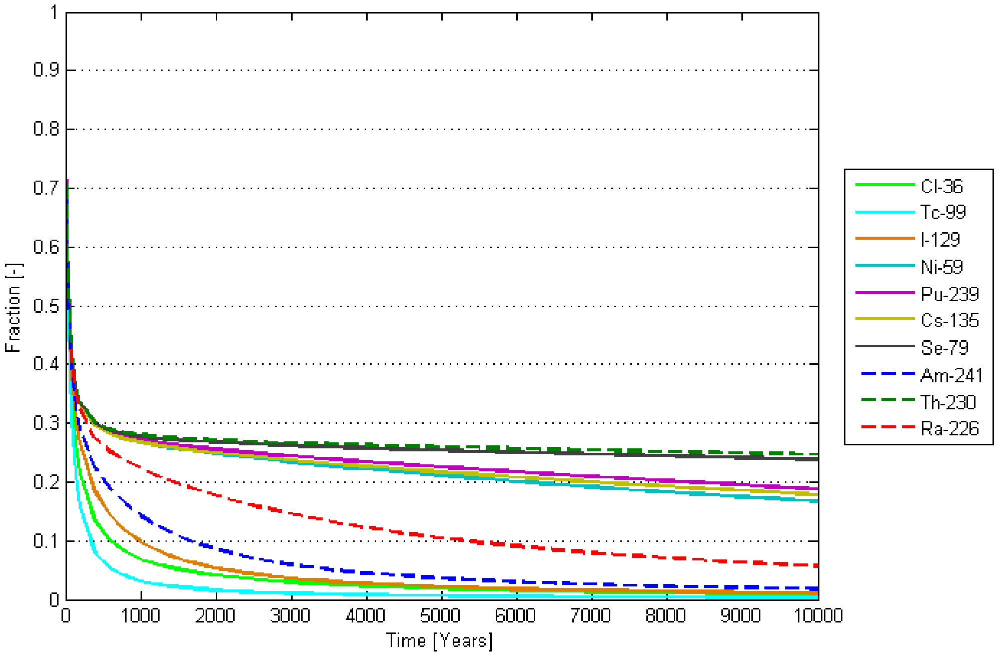


Figure 24. *Fraction of total release retained in system of the far future over time. The loss from the system is the amount in the Baltic Sea and the dilution from it, as well as the loss due to radioactive decay.*

case by demonstrating that predicted doses do not drastically depend on models and assumptions for landscape development. In view of the importance of this conclusion, it will require to be confirmed by further modelling based on an improved data basis.

- The relative importance of different radionuclides does not change between different landscape configurations. In all cases, landscape dose conversion factors (LDF's) based on a given release rate in Bq/yr have the highest values for the radionuclides Ra-226, Cs-135 and I-129. Also, the LDF's derived for the other radionuclides show, in general, the same relative importance for all analysed landscape configurations. This ranking of the importance of different radionuclides, of course, does not indicate which radionuclides actually are dominating predicted doses because these also depend on the actual source terms.
- In all landscape configurations, forests are dominating the dose contributions. This can be explained by a high release fraction to the forest objects as compared to other objects because those are located downstream in the landscape and have a large catchment area. Furthermore, the dilution of released radionuclides is lower in forest as compared to, for example, rivers and lakes. This finding should be considered in the further biosphere assessment programme.
- For Am-241, Pu-239 and Th-230, the transfer of radionuclides to biota is of lesser importance than for the other radionuclides. Instead, the direct ingestion of drinking water is more relevant and, consequently, lake and river objects are of higher relative importance compared to the forest objects. This aspect should be investigated in more detail in the further modelling.
- For mobile radionuclides such as iodine and technetium, equilibrium of the concentrations and resulting doses over time is achieved very fast. For less mobile elements, they increase over a period of a few thousand years and reach their equilibrium values then. Significant increases of the concentrations and doses with time beyond this period only occur for a few radionuclides.
- The fraction of the total release retained in the system depends on mobility and half-life. Mobile elements such as chlorine, iodine and technetium are released for all landscape configurations relatively fast into the Baltic Sea. For less mobile radionuclides such as Am-241 and Ra-226, the dominating losses from the system occur through radioactive decay. Long-lived radionuclides with relatively low mobility such as Th-230 and Se-79 are retained in the system to a large extent. Only for these radionuclides, accumulation plays a major role as can be seen from the development of concentrations with time. For all other radionuclides, i.e. either mobile radionuclides or radionuclides with relatively short half-life, accumulation effects are not of great importance. A further investigation of these effects for longer time scales is discussed in section 6.6 below.

These results provide a first answer to the objective of the report to investigate the impact of different landscape configurations on the predicted doses. It can be concluded that this impact is not such decisive that potential deficiencies in estimates of future landscapes would invalidate the results of the dose assessment. Results are relatively stable against changes in landscape.

This does not imply, however, that the consideration of future landscape configurations is unnecessary, because there are relevant quantitative differences between the results for different landscape configurations. Thus, their consideration comprises an important element in the derivation of quantitative predictions. But the qualitative stability of the results against changes of landscapes suggests that the principle uncertainties of future developments of landscapes do not preclude defining bounding calculation cases without having to choose overly conservative assumptions. As stated above, this conclusion will require to be further investigated for a model with dynamic transitions of landscape configurations.

The results also can be used to address the additional objective to identify the relevant radionuclides to be considered. This, however, also has to take account of actually expected source terms.

The further objective to investigate the effect of the accumulation of radionuclides in landscape objects also has been addressed above. In further modelling it may be required to re-investigate this aspect in more detail if it turns out that those radionuclides for which accumulation is relevant are important for the overall results of the assessment.

6.2 Uncertainty analysis

This section analyses the findings from the central calculation case in terms of prevailing parameter distributions. Also, an indication of the level of uncertainty which persists in the estimated landscape dose conversion factors is provided. However, only radionuclide-independent parameters and Kd values have been addressed in the analysis. Therefore, the results of this analysis provide some indication of parameter variability, but do not fully represent all parameters affecting to the derived landscape dose conversion factors. Further, model uncertainties are also not addressed at this stage.

In the following, results from probabilistic simulations for the total dose and for the averaged dose over all landscape objects are provided for each landscape configuration. The probability distributions are based on estimates of the parameter uncertainties given in the Appendices A and B.

For each result set, the mean and median values as well as minimum and maximum values occurring in the probabilistic simulations are given. To indicate the interval in which results are expected with high probability, 5th and 95th percentiles are given as well.

The results (Tables 9-16) show that the difference between 5th and 95th percentiles is at maximum three orders of magnitude. For some radionuclides such as Ra-226 differences in terms of landscape dose conversion factors are substantially smaller (factor of about 5). However, the limitations of this uncertainty analysis stated above have to be considered. Actual uncertainties of the current results will be larger.

Present landscape

Table 9. *Statistics of the results for the probabilistic simulation for the total dose (DTotMax) for the present landscape.*

Nuclide	**Mean**	**Median**	**Minimum**	**Maximum**	**5th perc.**	**95th perc.**
Cl-36	1.909e-012	7.0348e-013	2.9296e-015	2.8655e-011	3.1244e-014	7.8115e-012
Tc-99	1.1296e-012	9.4809e-014	2.1722e-016	9.2278e-012	1.9779e-015	3.9618e-012
I-129	1.3462e-010	4.3873e-011	8.1102e-014	1.0806e-009	1.2788e-012	4.5109e-010
Ni-59	4.9653e-014	4.1154e-014	1.3722e-015	3.3776e-013	8.2389e-015	1.1992e-013
Pu-239	2.8667e-013	2.5174e-013	4.8742e-014	1.4192e-012	1.1871e-013	5.7662e-013
Cs-135	2.0376e-011	1.6804e-011	1.6438e-012	1.1869e-010	4.8715e-012	4.7636e-011
Se-79	1.5199e-012	1.0812e-012	7.2756e-014	2.1141e-011	1.7561e-013	4.3239e-012
Am-241	1.9925e-013	1.9257e-013	1.125e-013	3.8038e-013	1.321e-013	2.9185e-013
Th-230	7.987e-013	7.0526e-013	1.1922e-013	3.9756e-012	3.3166e-013	1.5964e-012
Ra-226	2.8878e-010	2.5359e-010	3.073e-011	1.7151e-009	1.1241e-010	5.9231e-010

Table 10. *Statistics of the results for the probabilistic simulation for the average dose (DTotMean) for the present landscape.*

Nuclide	**Mean**	**Median**	**Minimum**	**Maximum**	**5th perc.**	**95th perc.**
Cl-36	1.2888e-015	5.6701e-016	2.9345e-018	1.2795e-014	2.5574e-017	4.7712e-015
Tc-99	7.886e-016	1.0124e-016	1.2937e-017	4.3481e-015	2.221e-017	2.3294e-015
I-129	1.0176e-013	4.2134e-014	2.9594e-015	5.0818e-013	4.8525e-015	2.8192e-013
Ni-59	5.6315e-017	5.4857e-017	1.5891e-017	1.5931e-016	2.7802e-017	9.193e-017
Pu-239	1.9618e-013	1.7861e-013	2.544e-014	8.1776e-013	9.7427e-014	3.6059e-013
Cs-135	1.4181e-014	1.2592e-014	1.6108e-015	6.2612e-014	4.4502e-015	2.9483e-014
Se-79	1.411e-014	1.3557e-014	5.8352e-015	3.2717e-014	8.902e-015	2.1457e-014
Am-241	3.5935e-014	3.4574e-014	1.6544e-014	1.0233e-013	2.3693e-014	5.2585e-014
Th-230	1.7486e-013	1.5921e-013	4.1187e-014	7.3156e-013	8.7383e-014	3.1793e-013
Ra-226	3.2375e-013	2.7308e-013	7.8204e-014	5.4211e-011	1.6158e-013	4.9014e-013

Landscape of first larger lakes

Table 11. *Statistics of the results for the probabilistic simulation for the total dose (DTotMax) for the landscape of first larger lakes.*

Nuclide	**Mean**	**Median**	**Minimum**	**Maximum**	**5th perc.**	**95th perc.**
Cl-36	1.1663e-012	4.511e-013	1.8289e-015	2.0395e-011	1.9958e-014	4.3424e-012
Tc-99	6.9892e-013	5.9763e-014	9.471e-017	8.6322e-012	1.4413e-015	2.4166e-012
I-129	8.3798e-011	2.746e-011	9.3891e-014	1.0216e-009	7.4586e-013	2.7466e-010
Ni-59	3.173e-014	2.6591e-014	6.0763e-016	2.6478e-013	5.6849e-015	7.4476e-014
Pu-239	1.8416e-013	1.5706e-013	2.5023e-014	1.1255e-012	7.8643e-014	3.8003e-013
Cs-135	1.2979e-011	1.0325e-011	1.4191e-012	1.4988e-010	3.1663e-012	3.1554e-011
Se-79	9.5897e-013	7.0436e-013	1.8232e-014	1.1361e-011	1.1138e-013	2.6726e-012
Am-241	2.7387e-014	2.6268e-014	1.4982e-014	8.7798e-014	1.7514e-014	4.1199e-014
Th-230	5.1097e-013	4.3963e-013	9.8915e-014	3.1962e-012	2.2036e-013	1.0579e-012
Ra-226	1.8432e-010	1.568e-010	3.032e-011	1.304e-009	7.4901e-011	3.8235e-010

Table 12. *Statistics of the results for the probabilistic simulation for the average dose (DTotMean) for the landscape of first larger lakes.*

Nuclide	**Mean**	**Median**	**Minimum**	**Maximum**	**5th perc.**	**95th perc.**
Cl-36	1.1663e-012	4.511e-013	1.8289e-015	2.0395e-011	1.9958e-014	4.3424e-012
Tc-99	6.9892e-013	5.9763e-014	9.471e-017	8.6322e-012	1.4413e-015	2.4166e-012
I-129	8.3798e-011	2.746e-011	9.3891e-014	1.0216e-009	7.4586e-013	2.7466e-010
Ni-59	3.173e-014	2.6591e-014	6.0763e-016	2.6478e-013	5.6849e-015	7.4476e-014
Pu-239	1.8416e-013	1.5706e-013	2.5023e-014	1.1255e-012	7.8643e-014	3.8003e-013
Cs-135	1.2979e-011	1.0325e-011	1.4191e-012	1.4988e-010	3.1663e-012	3.1554e-011
Se-79	9.5897e-013	7.0436e-013	1.8232e-014	1.1361e-011	1.1138e-013	2.6726e-012
Am-241	2.7387e-014	2.6268e-014	1.4982e-014	8.7798e-014	1.7514e-014	4.1199e-014
Th-230	5.1097e-013	4.3963e-013	9.8915e-014	3.1962e-012	2.2036e-013	1.0579e-012
Ra-226	2.5519e-013	2.3794e-013	6.4005e-014	4.5334e-012	1.3876e-013	4.178e-013

Landscape of young inland site

Table 13. *Statistics of the results for the probabilistic simulation for the total dose (DTotMax) for the landscape of young inland site.*

Nuclide	Mean	Median	Minimum	Maximum	5th perc.	95th perc.
Cl-36	1.0959e-012	4.2935e-013	2.1187e-015	2.1167e-011	1.8608e-014	4.1846e-012
Tc-99	6.6695e-013	5.6265e-014	1.0282e-016	8.9071e-012	1.3898e-015	2.3166e-012
I-129	7.9706e-011	2.5953e-011	8.9343e-014	1.0572e-009	7.537e-013	2.6362e-010
Ni-59	3.004e-014	2.4791e-014	5.4891e-016	2.9096e-013	5.1644e-015	7.2151e-014
Pu-239	1.728e-013	1.481e-013	3.07e-014	1.2248e-012	7.4303e-014	3.5982e-013
Cs-135	1.222e-011	9.7153e-012	9.2688e-013	1.0814e-010	3.0065e-012	2.9538e-011
Se-79	9.0655e-013	6.6184e-013	1.6012e-014	1.5941e-011	9.6529e-014	2.4718e-012
Am-241	2.5467e-014	2.4451e-014	1.3712e-014	9.2003e-014	1.6217e-014	3.8392e-014
Th-230	4.8024e-013	4.1208e-013	7.9606e-014	3.4599e-012	2.0738e-013	9.886e-013
Ra-226	1.7379e-010	1.479e-010	1.3431e-011	1.2001e-009	6.9152e-011	3.6144e-010

Table 14. *Statistics of the results for the probabilistic simulation for the average dose (DTotMean) for the landscape of young inland site.*

Nuclide	Mean	Median	Minimum	Maximum	5th perc.	95th perc.
Cl-36	1.318e-015	6.2976e-016	1.1256e-017	1.2758e-014	3.9883e-017	4.7891e-015
Tc-99	7.8885e-016	9.0309e-017	2.6953e-018	5.9268e-015	6.0476e-018	2.3269e-015
I-129	1.0166e-013	4.3364e-014	2.4668e-015	6.4826e-013	5.8166e-015	2.8132e-013
Ni-59	3.8383e-017	3.7062e-017	2.9047e-018	1.5489e-016	9.58e-018	7.3896e-017
Pu-239	6.4894e-014	5.8381e-014	6.6601e-015	3.7602e-013	3.2952e-014	1.1907e-013
Cs-135	1.8299e-014	1.6626e-014	4.081e-015	6.6331e-014	7.8404e-015	3.439e-014
Se-79	2.5095e-015	2.3477e-015	8.4738e-016	8.2755e-015	1.3865e-015	4.1986e-015
Am-241	6.5924e-015	6.0546e-015	2.8612e-015	2.9963e-014	3.9847e-015	1.1005e-014
Th-230	6.1346e-014	5.5624e-014	1.0911e-014	3.4312e-013	3.2887e-014	1.0902e-013
Ra-226	2.306e-013	2.1636e-013	4.2616e-014	2.7794e-012	1.2361e-013	3.8536e-013

Landscape of far future

Table 15. *Statistics of the results for the probabilistic simulation for the total dose (DTotMax) for the landscape of far future.*

Nuclide	Mean	Median	Minimum	Maximum	5th perc.	95th perc.
Cl-36	1.1109e-012	4.3603e-013	2.3696e-015	1.8918e-011	1.8403e-014	4.1686e-012
Tc-99	6.7501e-013	5.9145e-014	1.2064e-016	7.3434e-012	1.3836e-015	2.4074e-012
I-129	8.0942e-011	2.9344e-011	8.1758e-014	8.4426e-010	6.7176e-013	2.7277e-010
Ni-59	3.0262e-014	2.5147e-014	7.4506e-016	2.1099e-013	5.1323e-015	7.2889e-014
Pu-239	1.7601e-013	1.5039e-013	2.3239e-014	9.8297e-013	7.5426e-014	3.6809e-013
Cs-135	1.2296e-011	9.8864e-012	1.0962e-012	1.1289e-010	2.9412e-012	2.9862e-011
Se-79	9.1548e-013	6.5334e-013	1.7925e-014	9.2609e-012	9.6227e-014	2.5801e-012
Am-241	2.6025e-014	2.4984e-014	1.3961e-014	9.0669e-014	1.6572e-014	3.9341e-014
Th-230	4.865e-013	4.1679e-013	9.6308e-014	2.518e-012	2.0863e-013	1.0163e-012
Ra-226	1.7598e-010	1.5006e-010	1.8732e-011	1.0112e-009	7.0126e-011	3.7162e-010

Table 16. *Statistics of the results for the probabilistic simulation for the average dose (DTotMean) for the landscape of far future.*

Nuclide	Mean	Median	Minimum	Maximum	5th perc.	95th perc.
Cl-36	1.429e-015	6.8598e-016	1.2849e-017	1.3978e-014	4.1945e-017	5.1375e-015
Tc-99	8.6161e-016	1.0084e-016	2.9392e-018	5.6081e-015	6.78e-018	2.6305e-015
I-129	1.1069e-013	5.267e-014	2.4392e-015	6.92e-013	6.099e-015	3.0913e-013
Ni-59	4.1638e-017	4.0277e-017	2.5356e-018	1.8564e-016	1.0006e-017	8.1314e-017
Pu-239	5.4219e-014	4.8839e-014	7.044e-015	2.2301e-013	2.7555e-014	1.0039e-013
Cs-135	1.9896e-014	1.8026e-014	4.1942e-015	7.9814e-014	8.3234e-015	3.6857e-014
Se-79	2.6795e-015	2.4915e-015	7.7111e-016	8.9599e-015	1.4037e-015	4.5709e-015
Am-241	5.872e-015	5.4638e-015	2.5782e-015	2.2127e-014	3.6545e-015	9.5636e-015
Th-230	5.1969e-014	4.7251e-014	1.2494e-014	2.0621e-013	2.8173e-014	9.1718e-014
Ra-226	2.5669e-013	2.4188e-013	6.4339e-014	2.9108e-012	1.408e-013	4.2113e-013

6.3 Sensitivity analysis

The main aim of the sensitivity analysis is to identify important model parameters and assumptions with the aim of providing guidance to the scope and priorities of site investigation programmes and for the further development and refinement of the modelling. This is also one of the key objectives of the current report.

As described in Chapter 5, the sensitivity analysis is carried out in two steps. First, in the screening step, parameters with only small impact on the model results are determined not requiring a detailed sensitivity analysis (section 6.3.1). Potentially relevant parameters are analysed more comprehensively using Sobol's method in section 6.3.2. The effect of parameter variations is illustrated using some examples of sensitive parameters in section 6.3.3.

6.3.1 Screening

The sensitivity of the model output to the parameters is investigated for all four landscape configurations in the following using the screening approaches of Garten and Morris (see Chapter 5). For the Morris method, the effect for a given parameter was calculated as the square root of the sum of the squares of the means and standard deviations, and normalized with respect to the sum of all parameter effects (Ekström & Broed 2006). Parameters with an effect above 1 % in either of the methods are indicated in a summary table for each landscape configuration.

The results of the screening analysis, based on both approaches which have been applied, show that model results are sensitive to a number of parameters. Qualitatively, the results of the two screening methods are in quite good agreement. Some results, however, are different because these methods address different effects within the model. This supports the approach taken to use both methods in parallel in order not to overlook an important parameter.

Of particular importance are values for transpiration, interception, soil Kd, as well as areas and catchment areas of the forest objects. This conclusion holds in general for all landscape configurations, although the details of the sensitivity results vary to some extent due to the different configuration of objects in the four calculation cases.

Due to limitations of the screening methods, the actual values in the tables cannot be interpreted as a reliable representation of parameter importance. This can only be derived from a detailed analysis presented in the following section.

Present landscape

Table 17. *Results from the simulations using the method of Garten for the case of present landscape.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood				0.02		0.57	0.84		0.03	0.41
Yearly production of understorey plants						0.01	0.04			
Tree lifetime						0.09	0.23			0.04
Volumetric water content in soil	0.02	0.05								
Transpiration	1.00	1.00	1.00	0.95	0.74	0.95	0.82		0.58	0.68
Gross sedimentation rate, sea								0.03		
Dry mass of surface sediment, sea								0.01		
Resuspension of surface sediment								0.02		
Precipitation rate	1.00	1.00	1.00	0.92	0.74	0.91	0.70		0.43	0.56
Yearly production of tree leaves						0.06	0.32			0.08
Interception fraction	1.00	1.00	1.00	0.93	0.74	0.93	0.75		0.49	0.61
Thickness of soil rooting layer				0.37	0.55	0.30	0.39		0.71	0.64
Flow rate of Lapinjoki								0.69		
Flow rate of Eurajoki								0.05		
Bulk density of forest soil	0.01	0.03		0.22	0.37	0.18	0.24		0.49	0.44
Average depth of inner coast 3								0.06		
Area of inner coast 3								0.05		
Average depth of inner coast 2								0.05		
Area of inner coast 2								0.02		
Average depth of inner coast 1								0.06		
Area of inner coast 1								0.05		
Catchment area of southern forest	0.69	0.69	0.69							
Catchment area of northern forest	0.93	0.93	0.93	0.62	0.42	0.61	0.28		0.12	0.20

***Table 17** (cont'd). Results from the simulations using the method of Garten for the case of present landscape.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Area of northern forest				0.57	0.71	0.58	0.76		0.81	0.79
Distribution coefficient for forest soil	0.99	1.00	1.00	0.86	0.73	0.70	0.87		0.52	0.63
Distribution coefficient for sea								0.07		
Concentration ratio from soil to tree wood						0.49	0.61		0.01	0.18
Concentration ratio from soil to understorey						0.06	0.04			
Concentration ratio from soil to tree leaves						0.01	0.06			0.01

***Table 18.** Results from the simulation using the method of Morris for the case of present landscape.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	17%	5%	4%	1%		19%	10%		1%	14%
Yearly production of understorey plants	2%					1%	1%			
Tree lifetime	5%	1%	1%			3%	2%			2%
Volumetric water content in soil										
Transpiration	11%	16%	19%	21%	8%	3%	6%		14%	5%
Gross sedimentation rate								10%		
Dry mass of surface sediment, sea								7%		
Resuspension of surface sediment								8%		
Precipitation rate		10%	5%	3%	2%		4%		3%	3%
Yearly production of tree leaves	3%					4%	6%			2%
Interception fraction	23%	20%	20%	15%	8%	12%	16%		9%	8%
Thickness of soil rooting layer	6%	10%	11%	14%	20%	9%	11%		19%	12%
Annual average flow rate of Lapinjoki								50%		
Annual average flow rate of Eurajoki								1%		

Table 18 *(cont'd). Results from the simulation using the method of Morris for the case of present landscape.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Bulk density of forest soil	1%	3%	5%	7%	9%	3%	2%		9%	11%
Average depth of inner coast 3								2%		
Area of inner coast 3								2%		
Average depth of inner coast 2								2%		
Area of inner coast 2								3%		
Average depth of inner coast 1								1%		
Area of inner coast 1								1%		
Catchment area of southern forest				2%						
Area of southern forest				2%	2%		2%		1%	
Catchment area of northern forest			1%	3%	5%	4%	6%		6%	2%
Area of northern forest	17%	18%	19%	23%	29%	17%	13%	2%	27%	19%
Distribution coefficient for forest soil	1%	5%	6%	6%	14%	4%	4%		6%	6%
Distribution coefficient for sea								7%		
Concentration ratio from soil to tree wood	5%	8%	5%	1%		15%	11%		2%	14%
Concentration ratio from soil to understorey	4%					3%	1%			
Concentration ratio from soil to tree leaves	2%					2%	4%			2%

Table 19. *Summary of the screening methods (Garten and Morris) for the present landscape. The table shows which parameters each of the two methods indicated as significant based on the criteria for each method: M+G = both Morris and Garten, G = Garten only, and M = Morris only.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	M	M	M	M+G		M+G	M+G		M+G	M+G
Yearly production of understorey plants	M					M+G	M+G			
Tree lifetime	M	M	M			M+G	M+G			M+G
Volumetric water content in soil	M+G	M+G								
Transpiration	M+G	M+G	M+G	M+G	M+G	M+G	M+G		M+G	M+G

Table 19 *(cont'd). Summary of the screening methods (Garten and Morris) for the present landscape. The table shows which parameters each of the two methods indicated as significant based on the criteria for each method: M+G = both Morris and Garten, G = Garten only, and M = Morris only.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Gross sedimentation rate								M+G		
Dry mass of surface sediment, sea								M+G		
Resuspension of surface sediment								M+G		
Precipitation rate	M+G	M+G	M+G	M+G	M+G	G	M+G		M+G	M+G
Yearly production of tree leaves	M					M+G	M+G			M+G
Interception fraction	M+G	M+G	M+G	M+G	M+G	M+G	M+G		M+G	M+G
Thickness of soil rooting layer	M	M	M	M+G	M+G	M+G	M+G		M+G	M+G
Annual average flow rate of Lapinjoki								M+G		
Annual average flow rate of Eurajoki								M+G		
Bulk density of forest soil	M+G	M+G	G	M+G	M+G	M+G	M+G		M+G	M+G
Average depth of inner coast 3								M+G		
Area of inner coast 3								M+G		
Average depth of inner coast 2								M+G		
Area of inner coast 2								M+G		
Average depth of inner coast 1								M+G		
Area of inner coast 1								M+G		
Catchment area of southern forest	M+G	M+G	M+G	M						
Area of southern forest				M	M		M		M	
Catchment area of northern forest	M+G	G	M+G	M+G	M+G	M+G	M+G		M+G	M+G
Area of northern forest	M	M	M	M+G	M+G	M+G	M+G	M	M+G	M+G
Distribution coefficient for forest soil	M+G	M+G	M+G	M+G	M+G	M+G	M+G		M+G	M+G
Distribution coefficient for sea								M+G		
Concentration ratio from soil to tree wood	M	M	M	M		M+G	M+G		M+G	M+G
Concentration ratio from soil to understorey	M					M+G	M+G			
Concentration ratio from soil to tree leaves	M					M+G	M+G			M+G

Landscape of first larger lakes

Table 20. *Results from the simulations using the method of Garten for the landscape of first larger lakes.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.01			0.03		0.64	0.85		0.04	0.43
Yearly production of understorey plants						0.02	0.05			0.01
Tree lifetime						0.11	0.24			0.04
Volumetric water content in soil	0.02	0.05								
Transpiration	1.00	1.00	1.00	0.93	0.75	0.92	0.74	0.04	0.46	0.59
Precipitation rate	1.00	1.00	1.00	0.88	0.74	0.87	0.60	0.03	0.32	0.46
Yearly production of tree leaves						0.07	0.34			0.09
Interception fraction	1.00	1.00	1.00	0.90	0.75	0.89	0.65	0.03	0.37	0.51
Thickness of soil rooting layer				0.47	0.62	0.39	0.42		0.72	0.66
Annual average flow rate of Lapinjoki								0.72		
Bulk density of forest soil	0.01	0.04		0.31	0.42	0.24	0.26		0.51	0.45
Area of Inner coast 3								0.04		
Area of southern forest					0.06					
Catchment area of northern forest	0.96	0.96	0.96	0.52	0.32	0.50	0.20		0.08	0.15
Area of northern forest				0.58	0.75	0.60	0.81	0.43	0.86	0.84
Distribution coefficient for forest soil	0.99	1.00	1.00	0.80	0.74	0.59	0.82		0.40	0.53
Concentration ratio from soil to tree wood				0.01		0.56	0.64		0.01	0.18
Concentration ratio from soil to understorey						0.08	0.05			
Concentration ratio from soil to tree leaves						0.01	0.07			0.01

Table 21. *Results from the simulations using the method of Morris for the landscape of first larger lakes.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	19%	5%	2%	1%		20%	11%		1%	8%
Yearly production of understorey plants	1%					3%				
Tree lifetime	2%					1%	1%			2%
Volumetric water content in soil										
Transpiration	12%	14%	11%	8%	3%	2%	5%	1%	4%	11%
Precipitation rate	29%	25%	22%	20%	7%	21%	33%	1%	14%	8%
Yearly production of tree leaves	5%					2%	4%			2%
Interception fraction	7%	17%	20%	19%	18%	2%	6%	1%	16%	7%
Thickness of soil rooting layer	3%	8%	13%	16%	19%	6%	5%	21%	18%	10%
Annual average flow rate of Lapinjoki								13%		
Bulk density of forest soil	2%	7%	7%	9%	11%	3%	2%	13%	11%	9%
Water retention time of Inner coast 3								4%		
Average depth of Inner coast 3								8%		
Area of Inner coast 3								8%		
Catchment area of southern forest					1%					
Area of southern forest					2%			1%		
Catchment area of northern forest	1%		2%	5%	5%	5%	3%		7%	2%
Area of northern forest	10%	16%	15%	17%	21%	18%	7%	25%	23%	21%
Distribution coefficient for forest soil			2%	2%	12%	4%	2%		4%	5%
Concentration ratio from soil to tree wood	2%	2%	3%	2%		10%	12%		1%	11%
Concentration ratio from soil to understorey	1%									
Concentration ratio from soil to tree leaves	6%	2%	2%			3%	6%			4%

Table 22. *Summary of the screening methods (Garten and Morris) for the landscape of first larger lakes. The table shows which parameters each of the two methods indicated as significant based on the criteria for each method: M+G = both Morris and Garten, G = Garten only, and M = Morris only.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	M+G	M	M	M+G		M+G	M+G		M+G	M+G
Yearly production of understorey plants	M					M+G	G			G
Tree lifetime	M					M+G	M+G			M+G
Volumetric water content in soil	G	G								
Transpiration	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Precipitation rate	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Yearly production of tree leaves						M+G	M+G			M+G
Interception fraction	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Thickness of soil rooting layer	M	M	M	M+G	M+G	M+G	M+G	M	M+G	M+G
Annual average flow rate of Lapinjoki								M+G		
Bulk density of forest soil	M+G	M+G	M	M+G	M+G	M+G	M+G	M	M+G	M+G
Water retention time of Inner coast 3								M		
Average depth of Inner coast 3								M+G		
Area of Inner coast 3								M		
Catchment area of southern forest					M					
Area of southern forest					M+G			M		
Catchment area of northern forest	M+G	G	M+G	M+G	M+G	M+G	M+G		M+G	M+G
Area of northern forest	M	M	M	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Distribution coefficient for forest soil	G	G	M+G	M+G	M+G	M+G	M+G		M+G	M+G
Concentration ratio from soil to tree wood	M			G		G	G		M+G	M+G
Concentration ratio from soil to understorey	M					G	G			
Concentration ratio from soil to tree leaves	M	M	M			M+G	M+G			M+G

Landscape of young inland site

Table 23. Results from the simulations using the method of Garten for the landscape of young inland site.

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.01			0.03		0.64	0.85		0.04	0.43
Yearly production of understorey plants						0.02	0.05			0.01
Tree lifetime						0.11	0.24			0.04
Volumetric water content in soil	0.02	0.05								
Transpiration	1.00	1.00	1.00	0.93	0.75	0.92	0.74	0.04	0.46	0.59
Precipitation rate	1.00	1.00	1.00	0.88	0.74	0.87	0.60	0.03	0.32	0.46
Yearly production of tree leaves						0.07	0.34			0.09
Interception fraction	1.00	1.00	1.00	0.90	0.75	0.89	0.65	0.03	0.37	0.51
Thickness of soil rooting layer				0.47	0.62	0.39	0.42		0.72	0.66
Annual average flow rate of Lapinjoki								0.72		
Bulk density of forest soil	0.01	0.04		0.31	0.42	0.24	0.26		0.51	0.45
Catchment area of northern forest	0.96	0.96	0.96	0.52	0.32	0.50	0.20		0.08	0.15
Area of northern forest				0.58	0.75	0.60	0.81	0.43	0.86	0.84
Distribution coefficient for forest soil	0.99	1.00	1.00	0.80	0.74	0.59	0.82		0.40	0.53
Concentration ratio from soil to tree wood				0.01		0.56	0.64		0.01	0.18
Concentration ratio from soil to understorey						0.08	0.05			
Concentration ratio from soil to tree leaves						0.01	0.07			0.01

__Table 24.__ Results from the simulations using the method of Morris for the landscape of young inland site.

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	10%	4%	3%	1%		15%	11%			7%
Yearly production of understorey plants						2%				
Tree lifetime	4%	4%	3%	1%		3%	5%			2%
Volumetric water content in soil	4%	9%	8%	5%	6%	7%	4%	2%	4%	4%
Transpiration	9%	14%	13%	15%	5%	4%	8%	1%	11%	5%
Precipitation rate	11%	4%	3%			5%	18%			2%
Yearly production of tree leaves	19%	25%	23%	22%	16%	12%	12%	2%	12%	7%
Interception fraction	5%	8%	11%	12%	20%	5%	1%	23%	19%	17%
Thickness of soil rooting layer								20%		
Annual average flow rate of Lapinjoki	3%	6%	6%	8%	9%	2%	3%	9%	9%	9%
Bulk density of forest soil	1%		2%	4%	2%	2%	5%	1%	3%	3%
Catchment area of northern forest					2%					
Area of northern forest	13%	17%	20%	22%	29%	11%	12%	32%	29%	25%
Distribution coefficient for forest soil	2%			6%	11%	6%	3%	5%	8%	4%
Concentration ratio from soil to tree wood	8%	4%	6%	2%		10%	8%		2%	13%
Concentration ratio from soil to understorey	11%					13%	4%			
Concentration ratio from soil to tree leaves			1%			2%	6%			2%

Table 25. Summary of the screening methods (Garten and Morris) for the landscape of first larger lakes. The table shows which parameters each of the two methods indicated as significant based on the criteria for each method: M+G = both Morris and Garten, G = Garten only, and M = Morris only.

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	M+G	M	M	G		M+G	M+G		G	M+G
Yearly production of understorey plants						G	G			G
Tree lifetime	M	M	M			M+G	M+G			M+G
Volumetric water content in soil	G	G								
Transpiration	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Precipitation rate	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Yearly production of tree leaves	M	M	M			M+G	M+G			M+G
Interception fraction	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Thickness of soil rooting layer	M	M	M	M+G	M+G	M+G	M+G	M	M+G	M+G
Annual average flow rate of Lapinjoki								M+G		
Bulk density of peat soil								M+G		
Bulk density of forest soil	M+G	M+G	M	M+G	M+G	M+G	M+G	M	M+G	M+G
Catchment area of northern forest	M+G	G	M+G	M+G	M+G	M+G	M+G	M	M+G	M+G
Area of southern forest					M					
Area of northern forest	M	M	M	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Distribution coefficient for forest soil	M+G	G	M+G	M+G	M+G	M+G	M+G	M	M+G	M+G
Concentration ratio from soil to tree wood	M	M	M	M+G		M+G	M+G		M+G	M+G
Concentration ratio from soil to understorey	M					M+G	M+G			
Concentration ratio from soil to tree leaves						M+G	M+G			

Landscape of far future

Table 26. *Results from the simulations using the method of Garten for the landscape of far future.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.01			0.03		0.64	0.85		0.04	0.43
Yearly production of understorey plants						0.02	0.05			0.01
Tree lifetime						0.11	0.24			0.04
Volumetric water content in soil	0.02	0.05								
Transpiration	1.00	1.00	1.00	0.93	0.75	0.92	0.74	0.04	0.46	0.59
Precipitation rate	1.00	1.00	1.00	0.88	0.74	0.87	0.60	0.03	0.32	0.46
Yearly production of tree leaves						0.07	0.34			0.09
Interception fraction	1.00	1.00	1.00	0.90	0.74	0.89	0.65	0.03	0.37	0.51
Thickness of soil rooting layer				0.47	0.62	0.39	0.42		0.72	0.66
Annual average flow rate of Lapinjoki								0.72		
Bulk density of forest soil	0.01	0.04		0.31	0.42	0.24	0.26		0.51	0.45
Average depth of Liiklansuo								0.01		
Area of southern forest					0.10					
Catchment area of northern forest	0.96	0.96	0.96	0.52	0.32	0.50	0.20		0.08	0.15
Area of northern forest				0.58	0.75	0.60	0.81	0.42	0.86	0.84
Distribution coefficient for forest soil	0.99	1.00	1.00	0.80	0.74	0.59	0.82		0.40	0.53
Concentration ratio from soil to tree wood				0.01		0.56	0.64		0.01	0.18
Concentration ratio from soil to understorey						0.08	0.05			0.01
Concentration ratio from soil to tree leaves						0.01	0.07			0.01

Table 27. *Results from the simulations using the method of Morris for the landscape of far future.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	5.8%	2.3%	1.6%			10.9%	7.6%		1.4%	10%
Yearly production of understorey plants	2.2%					3.0%				
Tree lifetime	1.4%	1.4%	1.1%			1.7%	1.3%			3%
Transpiration	20.0%	31.4%	29.3%	24.6%	6.4%	4.6%	10.6%		11.2%	8%
Precipitation rate	8.1%	8.5%	11.3%	10.9%	4.8%	6.3%	2.4%		5.1%	8%
Yearly production of tree leaves	1.5%	6.6%				2.9%	11.3%			4%
Interception fraction	18.7%	15.5%	15.2%	14.8%	6.4%	3.4%	4.8%	1.2%	5.4%	7%
Thickness of soil rooting layer	8.0%	12.3%	16.8%	18.7%	25.5%	13.4%	4.5%	28.4%	25.7%	14%
Annual average flow rate of Lapinjoki								17.7%		
Bulk density of forest soil		1.9%	3.5%	5.1%	9.4%	2.6%		16.2%	8.8%	6%
Area of southern forest					5.7%			4.1%		
Catchment area of northern forest	1.7%	1.5%	2.0%	4.3%	5.7%	7.4%	7.2%		12.9%	2%
Area of northern forest	17.4%	12.9%	12.9%	14.6%	23.0%	18.2%	18.8%	25.7%	22.2%	18%
Distribution coefficient for forest soil	1.1%		1.5%	3.2%	12.2%	8.4%	3.7%	1.9%	4.9%	6%
Concentration ratio from soil to tree wood	6.0%	3.8%	2.9%	1.7%		11.4%	24.2%		1.3%	12%
Concentration ratio from soil to understorey	7.5%					1.1%				
Concentration ratio from soil to tree leaves						4.6%	2.0%			1%

Table 28. *Summary of the screening methods (Garten and Morris) for the landscape of far future. The table shows which parameters each of the two methods indicated as significant based on the criteria for each method: M+G = both Morris and Garten, G = Garten only, and M = Morris only.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	M+G	M	M	G		M+G	M+G		M+G	M+G
Yearly production of understorey plants	M					M+G	G			G
Tree lifetime	M	M	M			M+G	M+G			M+G
Volumetric water content in soil	G	G								
Transpiration	M+G	M+G	M+G	M+G	M+G	M+G	M+G	G	M+G	M+G
Precipitation rate	M+G	M+G	M+G	M+G	M+G	M+G	M+G	G	M+G	M+G
Yearly production of tree leaves	M	M				M+G	M+G			M+G
Interception fraction	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Thickness of soil rooting layer	M	M	M	M+G	M+G	M+G	M+G	M	M+G	M+G
Annual average flow rate of Lapinjoki								M+G		
Bulk density of forest soil	G	M+G	M	M+G	M+G	M+G	G	M	M+G	M+G
Average depth of Liiklansuo								G		
Area of southern forest					M+G			M		
Catchment area of northern forest	M+G	M+G	M+G	M+G	M+G	M+G	M+G		M+G	M+G
Area of northern forest	M	M	M	M+G	M+G	M+G	M+G	M+G	M+G	M+G
Distribution coefficient for forest soil	M+G	G	M+G	M+G	M+G	M+G	M+G	M	M+G	M+G
Concentration ratio from soil to tree wood	M	M	M	M+G		M+G	M+G		M+G	M+G
Concentration ratio from soil to understorey	M					M+G	G			G
Concentration ratio from soil to tree leaves						M+G	M+G			M+G

6.3.2 Sensitivity by Sobol's method

The potentially relevant parameters identified by screening in the preceding section are analysed in depth using Sobol's method. Results are presented for the four landscape configurations in the following tables. Only results with a value of the total sensitivity index larger than 0.1 are shown. Parameters with the highest sensitivity for a given radionuclide are underlined in the tables.

The results essentially confirm that those parameters selected for further analysis based on the screening actually have relevant impacts on the model results. The degree of this impact, however, varies. For example it becomes apparent that the soil Kd only have relatively small impacts as opposed to the findings of the screening analysis.

The importance of parameters depends, as to be expected, on the radionuclide considered. Nevertheless, a few parameters (transpiration, interception and forest area) have a decisive impact for most radionuclides. Other parameters (e.g. the flow rate of the Lapinjoki river) are relevant only for one or a few radionuclides (Am-241 in this case).

These results suggest the following approach for the further improvement of the input data use and modelling:

- Parameter values relevant for several or all considered radionuclides require further consideration in any case. These should be addressed, to the extent possible, in measurement programmes. For parameters concerning future developments, which cannot be measured directly, adequate measures should be taken to reduce uncertainties and increase confidence (e.g. modelling, expert judgement).
- Parameters with a high sensitivity only for one or just a few radionuclides need special attention only if the contribution of this (or these) radionuclide(s) to the overall total dose estimates is relevant. This depends on the derived LDF's and on the actual release term. The planning for improvements of the input parameter data should consider these aspects in order to focus efforts on those factors which are relevant for the assessment results and for the confidence in those.
- To the same extent that attempts are made to improve input parameter data for relevant parameters, model equations and assumptions should be reviewed which affect the impact assessment aspects (e.g. exposure pathways) determined by these parameters. If this results in a further development and refinement of the models, a new sensitivity analysis would be required.

These findings of the sensitivity analysis are based on the current model and input parameter data used. After any of the planned improvements, a new sensitivity analysis will be required.

Table 29. *Total sensitivity indices (TSI) calculated using the Sobol method for the case of* ***present landscape****. The most important nuclide for each parameter is underlined.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.44					0.47	0.23			
Transpiration	0.47	0.61	0.59	0.37			0.18		0.12	
Precipitation rate	0.22	0.35	0.36	0.28	0.16				0.19	
Interception fraction	0.39	0.53	0.50	0.35			0.30			
Thickness of soil rooting layer				0.17	0.23				0.22	0.17
Bulk density of forest soil										0.16
Annual average flow rate of Lapinjoki								0.90		
Area of northern forest	0.14	0.22	0.27	0.40	0.61	0.23	0.12		0.62	0.49
Distribution coefficient for forest soil						0.13				
Concentration ratio from soil to tree wood						0.40	0.22			

Table 30. *Total sensitivity indices (TSI) calculated using the Sobol method for the case of* ***first larger lakes****. The most important nuclide for each parameter is underlined.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.18					0.26	0.12			
Transpiration	0.59	0.42	0.43	0.38			0.14		0.17	
Precipitation rate	0.39	0.26	0.26	0.20					0.12	
Interception fraction	0.37	0.48	0.47	0.29			0.27			0.11
Thickness of soil rooting layer		0.13	0.13	0.18	0.20		0.16		0.18	0.12
Annual average flow rate of Lapinjoki								1.06		
Bulk density of forest soil				0.10	0.16			0.12	0.16	
Area of northern forest	0.48	0.40	0.41	0.54	0.81	0.53	0.38	0.52	0.79	0.43
Distribution coefficient for forest soil						0.13				
Concentration ratio from soil to tree wood	0.17					0.27	0.22			0.17

***Table 31.** Total sensitivity indices (TSI) calculated using the Sobol method for the case of **young inland site**. The most important nuclide for each parameter is underlined.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.10					0.28				
Transpiration	0.28	0.28	0.27	0.16			0.19			
Precipitation rate	0.13	0.14	0.12				0.11			
Interception fraction	0.63	0.54	0.50	0.23			0.10			
Thickness of soil rooting layer			0.10	0.17	0.16		0.17	0.25	0.22	0.14
Annual average flow rate of Lapinjoki								1.23		
Bulk density of forest soil		0.14	0.16	0.25	0.34			0.27	0.33	0.13
Area of northern forest	0.29	0.31	0.33	0.45	0.67	0.44	0.14	0.38	0.70	0.56
Concentration ratio from soil to tree wood							0.63			
Distribution coefficient for forest soil										0.17

***Table 32.** Total sensitivity indices (TSI) calculated using the Sobol method for the case of **far future**. The most important nuclide for each parameter is underlined.*

Parameter	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Yearly production of tree wood	0.42					0.41	0.17			
Transpiration	0.46	0.47	0.47	0.30			0.21			
Precipitation rate	0.20	0.26	0.23	0.14			0.14			
Interception fraction	0.49	0.44	0.42	0.29			0.31			0.15
Thickness of soil rooting layer					0.24			0.14	0.19	0.15
Annual average flow rate of Lapinjoki								0.85		
Bulk density of forest soil					0.13				0.11	0.13
Area of northern forest	0.23	0.28	0.28	0.48	0.83	0.50	0.42	0.50	0.83	0.54
Distribution coefficient for forest soil				0.10	0.13				0.11	
Concentration ratio from soil to tree wood	0.17					0.31	0.35			0.16

6.3.3 Illustration of specific parameter sensitivities

The following figures provide some examples to illustrate the effect of parameter uncertainties for some of input parameters identified as most important in the preceding section:

- Figure 25 shows the effect on the total dose from I-129 of a variation of values for transpiration and interception for the landscape of first larger lakes.
- Figure 26 contains results for Ra-226 obtained by varying the soil Kd value for the landscape of young inland site.
- Figure 27 depicts the result for Cl-36 of varying the concentration ratio of nuclides from soil to tree wood (CR_W) and the annual wood production (WP) for the landscape of young inland site.

In each case, three values for each parameter have been used corresponding to the minimum, central and maximum value of the range provided in Appendix 1.

The large variations of the total doses in particular in Figure 23 demonstrate the importance of these parameters for the assessment results.

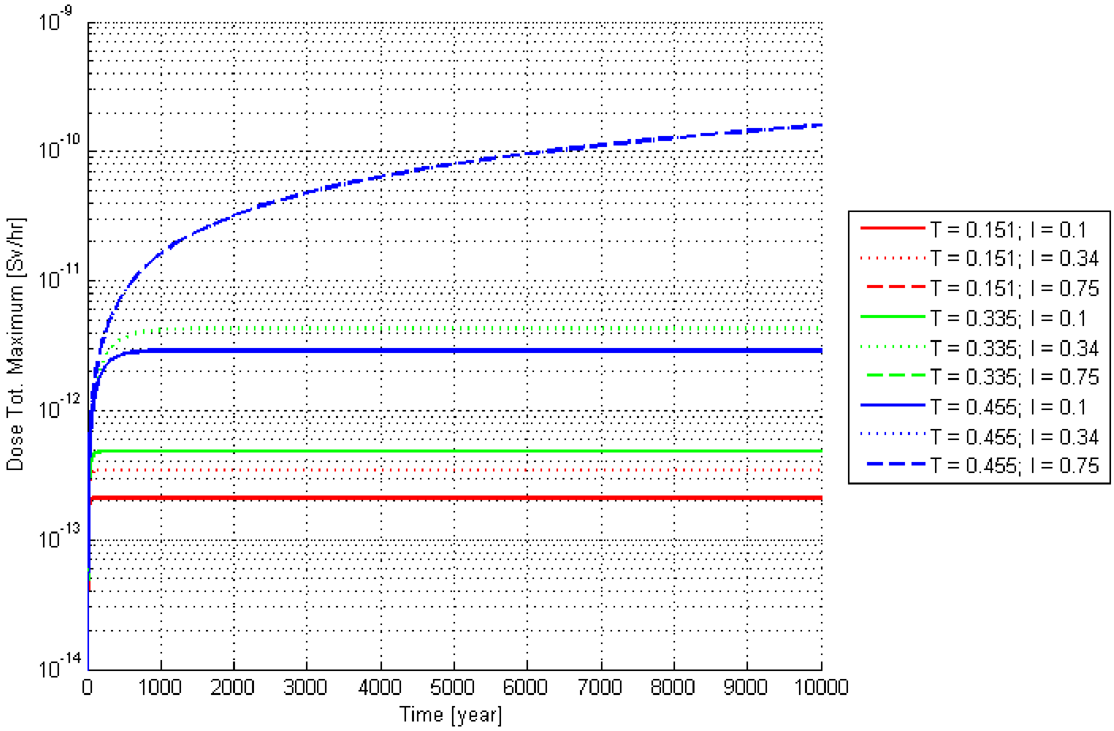


Figure 25. *The effect on the maximum total dose from I-129 of various combinations of values for transpiration and intercepted fraction for the landscape of first larger lakes.*

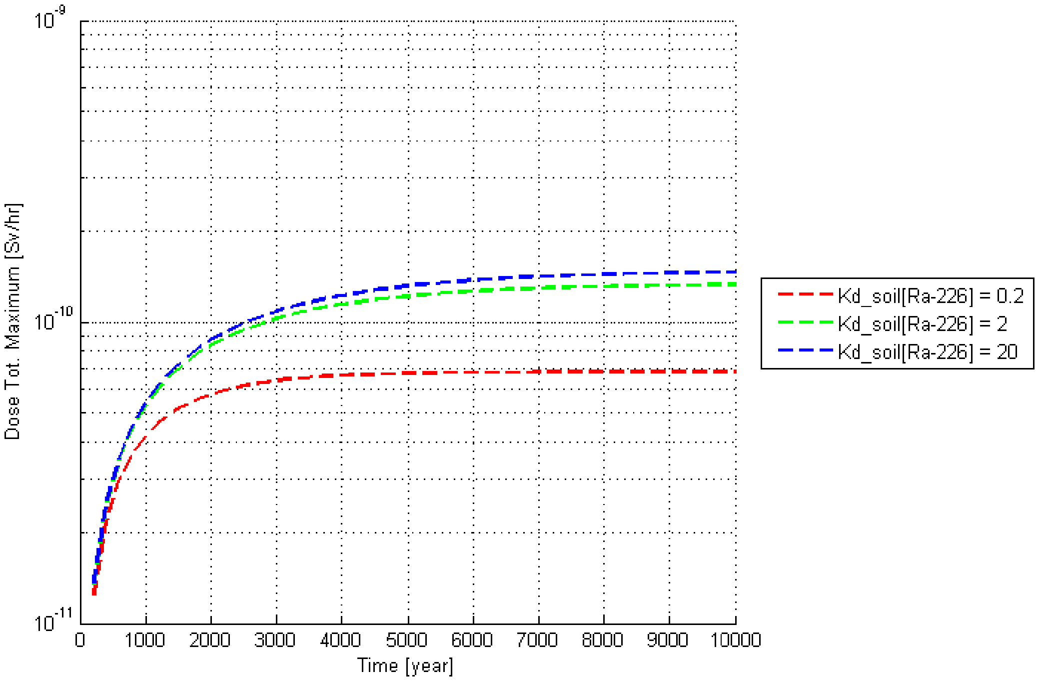


Figure 26. *Effect on the maximum total dose from Ra-226 of varying the distribution coefficient (Kd) of soil for the case of young inland site.*

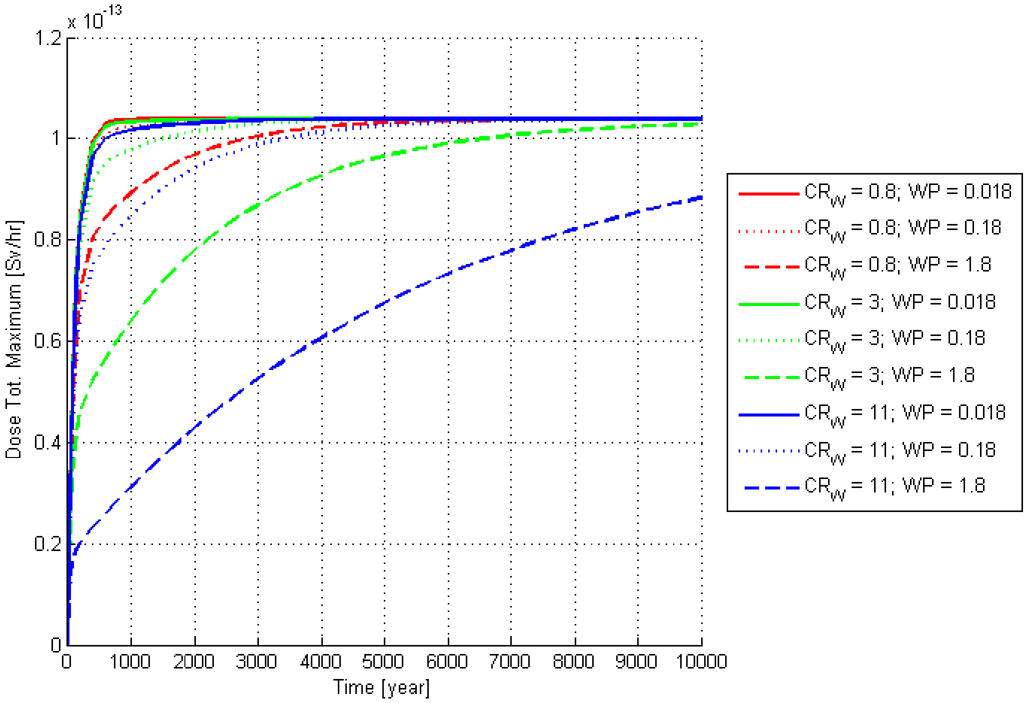


Figure 27. *Effect on the maximum total dose from Cl-36 of varying the concentration ratio of nuclides from soil to tree wood (CR_W) and the annual wood production (WP) for the case of young inland site.*

6.4 Variant cases

Several important objectives of the current report already have been addressed in the previous sections based on the results for the central case and the sensitivity analysis (dependence of model results on landscape configurations, identification of important parameters and model assumptions, radionuclides to be considered and effect of accumulation). Some specific questions raised in section 1.4, however, require particular calculations of variant cases as presented in the following:

- identification of the importance of different release point locations;
- effect of the assumptions on the geosphere-biosphere interface (GBI);
- effect of accumulation time.

For these variant calculations, the landscape of young inland site was selected for additional calculations. This landscape configuration was selected since

- it includes all biosphere object types and has more biosphere objects than the landscape configuration for the first larger lakes; and
- the site-specific data for this configuration have a higher level of confidence than those for the case of far future.

6.4.1 Different release point locations

In the first variant case, the total unit release (1 Bq/y) distributed to several objects in the central case was assumed to be an input only to one object at a time to study the effect of the location of the release area. In Tables 33 and 34, maximum and mean landscape doses are presented for each biosphere object receiving the total release.

Another case was included where no knowledge about the discharge points was assumed, and the same fraction was assumed to discharge to all objects. These results are shown in Tables 35 and 36. This table also shows the minimum and maximum values of the results in Tables 33…34 and compares them to the results of the central case calculations.

From Tables 35 and 36 it can be seen that the difference of the maximum values compared to the central case is one order of magnitude or less. A conservative model, assuming all releases to one object, therefore, would overestimate doses by one order of magnitude at maximum. Nevertheless, this overestimation should be avoided by assessing the discharge locations as well as possible. The results in Tables 33 and 34 can be used as guidance in this regard to determine which potential discharge locations have to be seen as particularly important. Also worth noting is that the case with equal discharge to all objects is slightly less conservative than the central case. This can be explained by the fact that for the central case the outer coast and the Baltic Sea receive a smaller fraction of the total release to the landscape, and therefore the residence time of radionuclides in the system is slightly higher.

Table 33. *Maximum landscape doses (DTotMax) for the variant assuming the unit release occurring only to one object of the landscape of young inland site.*

Object	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Forest N	5.20E-13	2.06E-14	2.04E-11	1.12E-13	5.96E-13	8.56E-11	6.98E-12	5.66E-14	2.10E-12	8.85E-10
Forest S	5.30E-16	3.13E-16	2.48E-13	2.91E-17	9.34E-13	8.87E-14	8.56E-15	7.85E-14	9.52E-13	1.19E-13
Kornanjärvi	1.57E-16	4.41E-17	7.34E-14	2.11E-17	2.56E-14	6.65E-14	1.93E-14	2.05E-14	7.03E-14	4.78E-14
Pätkä	1.57E-16	4.41E-17	7.34E-14	2.11E-17	2.56E-14	6.66E-14	1.93E-14	2.05E-14	7.04E-14	4.77E-14
Liiklansuo	5.33E-16	3.13E-16	2.49E-13	7.17E-17	8.69E-14	2.26E-13	6.55E-14	6.77E-14	2.39E-13	1.28E-12
Liiklanjärvi	6.26E-16	1.76E-16	2.92E-13	8.42E-17	1.02E-13	2.65E-13	7.68E-14	8.16E-14	2.80E-13	2.80E-13
Liponjärvi	6.10E-16	1.71E-16	2.85E-13	8.20E-17	9.93E-14	2.59E-13	7.49E-14	7.95E-14	2.73E-13	2.77E-13
Kiskarinjärvi	1.57E-16	4.41E-17	7.34E-14	2.11E-17	2.56E-14	6.66E-14	1.93E-14	2.05E-14	7.04E-14	4.77E-14
Susijoki	1.57E-16	4.40E-17	7.32E-14	2.11E-17	2.55E-14	6.64E-14	1.92E-14	2.04E-14	7.02E-14	4.76E-14
Susijärvi	1.57E-16	4.40E-17	7.32E-14	2.11E-17	2.55E-14	6.64E-14	1.92E-14	2.04E-14	7.01E-14	4.77E-14
Liponsuo	1.36E-19	2.82E-18	4.85E-16	2.78E-18	1.17E-15	5.86E-17	1.70E-15	2.92E-15	9.25E-16	3.86E-14
Pitkäjoki	1.57E-16	4.41E-17	7.34E-14	2.11E-17	2.56E-14	6.65E-14	1.93E-14	2.05E-14	7.04E-14	4.75E-14
Inner Coast 1	2.75E-19	5.69E-18	9.77E-16	5.59E-18	2.34E-15	1.18E-16	3.43E-15	5.91E-15	1.86E-15	4.43E-15
Inner Coast 2	2.82E-19	5.82E-18	1.00E-15	5.72E-18	2.39E-15	1.21E-16	3.51E-15	6.05E-15	1.90E-15	4.53E-15
Inner Coast 3	9.40E-19	1.94E-17	3.34E-15	1.91E-17	8.01E-15	4.04E-16	1.17E-14	2.02E-14	6.35E-15	1.45E-14
Inner Coast 4	6.20E-19	1.28E-17	2.20E-15	1.26E-17	5.28E-15	2.66E-16	7.72E-15	1.33E-14	4.19E-15	9.63E-15
Inner Coast 5	1.60E-19	3.31E-18	5.69E-16	3.26E-18	1.36E-15	6.88E-17	2.00E-15	3.45E-15	1.08E-15	2.69E-15

Table 34. *Mean landscape doses (DTotMean) for the variant assuming the unit release occurring only to one object of the landscape of young inland site.*

Object	**Cl-36**	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
Forest N	4.83E-16	2.16E-17	2.19E-14	1.06E-16	5.66E-13	7.96E-14	6.60E-15	5.42E-14	6.40E-13	8.64E-13
Forest S	1.01E-15	5.10E-17	5.17E-14	1.35E-16	3.13E-13	1.04E-13	7.39E-15	2.62E-14	2.40E-13	8.90E-13
Kornanjärvi	5.90E-18	3.14E-18	2.05E-15	1.20E-18	1.42E-15	1.55E-15	7.92E-16	1.55E-15	2.30E-15	2.45E-15
Pätkä	4.31E-18	2.49E-18	1.41E-15	9.41E-19	1.11E-15	1.01E-15	5.97E-16	1.24E-15	1.65E-15	2.18E-15
Liiklansuo	3.29E-17	1.28E-17	1.27E-14	4.35E-18	6.31E-15	1.07E-14	3.38E-15	5.23E-15	1.31E-14	8.89E-14
Liiklanjärvi	3.35E-17	1.29E-17	1.29E-14	4.32E-18	6.35E-15	1.09E-14	3.37E-15	5.34E-15	1.31E-14	2.07E-14
Liponjärvi	3.11E-17	1.23E-17	1.38E-14	4.16E-18	6.11E-15	1.16E-14	3.61E-15	5.86E-15	1.25E-14	2.02E-14
Kiskarinjärvi	4.32E-18	2.87E-18	1.63E-15	1.00E-18	1.06E-15	1.17E-15	6.68E-16	1.41E-15	1.89E-15	2.19E-15
Susijoki	4.39E-18	2.47E-18	1.38E-15	9.25E-19	1.09E-15	9.80E-16	5.82E-16	1.23E-15	1.60E-15	2.14E-15
Susijärvi	4.93E-18	2.89E-18	1.59E-15	1.08E-18	1.28E-15	1.12E-15	6.74E-16	1.23E-15	1.88E-15	2.15E-15
Liponsuo	2.22E-20	4.59E-19	7.89E-17	4.52E-19	1.90E-16	9.54E-18	2.77E-16	4.74E-16	1.51E-16	5.53E-15
Pitkäjoki	2.34E-18	1.90E-18	3.27E-16	5.18E-19	7.46E-16	1.16E-17	3.10E-16	9.45E-16	6.21E-16	1.35E-15
Inner Coast 1	2.78E-20	5.73E-19	9.86E-17	5.63E-19	2.32E-16	1.19E-17	3.45E-16	5.95E-16	1.84E-16	6.62E-16
Inner Coast 2	2.79E-20	5.76E-19	9.90E-17	5.66E-19	2.34E-16	1.19E-17	3.47E-16	5.98E-16	1.85E-16	6.64E-16
Inner Coast 3	2.80E-20	5.79E-19	9.95E-17	5.69E-19	2.36E-16	1.20E-17	3.49E-16	6.01E-16	1.87E-16	6.67E-16
Inner Coast 4	2.80E-20	5.79E-19	9.95E-17	5.69E-19	2.36E-16	1.20E-17	3.49E-16	6.01E-16	1.87E-16	6.67E-16
Inner Coast 5	2.55E-20	5.26E-19	9.04E-17	5.17E-19	2.14E-16	1.09E-17	3.17E-16	5.47E-16	1.70E-16	6.28E-16

Table 35. *Maximum landscape doses (DTotMax) for the variant assuming the unit release occurring equally to all objects in the landscape of young inland site compared to minimum and maximum value of the respective results in Table 33 and to the results of the respective central case.*

	Cl-36	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
All	3.06E-14	1.19E-15	1.20E-12	6.60E-15	5.49E-14	5.04E-12	4.10E-13	1.21E-14	1.24E-13	5.21E-11
Min	1.36E-19	2.82E-18	4.85E-16	2.78E-18	1.17E-15	5.86E-17	1.70E-15	2.92E-15	9.25E-16	2.69E-15
Max	5.20E-13	2.06E-14	2.04E-11	1.12E-13	9.34E-13	8.56E-11	6.98E-12	8.16E-14	2.10E-12	8.85E-10
Central Case	1.02E-13	3.98E-15	4.03E-12	2.21E-14	1.17E-13	1.69E-11	1.37E-12	2.74E-14	4.15E-13	1.74E-10

Table 36. *Mean landscape doses (DTotMean) for the variant assuming the unit release occurring equally to all objects in the landscape of young inland site compared to minimum and maximum value of the respective results in Table 34 and to the results of the respective central case.*

	Cl-36	**Tc-99**	**I-129**	**Ni-59**	**Pu-239**	**Cs-135**	**Se-79**	**Am-241**	**Th-230**	**Ra-226**
All	9.32E-17	6.19E-18	6.75E-15	1.52E-17	2.33E-14	1.30E-14	1.70E-15	3.16E-15	2.61E-14	1.08E-13
Min	2.22E-20	4.59E-19	7.89E-17	4.52E-19	1.90E-16	9.54E-18	2.77E-16	4.74E-16	1.51E-16	6.28E-16
Max	1.01E-15	5.10E-17	5.17E-14	1.35E-16	5.66E-13	1.04E-13	7.39E-15	5.42E-14	6.40E-13	8.90E-13
Central Case	1.72E-16	1.10E-17	1.25E-14	3.12E-17	4.54E-14	2.70E-14	3.28E-15	5.82E-15	5.25E-14	2.35E-13

6.4.2 Effect of the assumptions on geosphere-biosphere interface

In this variant calculation, the releases were not assumed to take place directly to the water bodies of the lakes and coast objects as in the previous module versions. Instead, a modified model was used, in which an additional compartment representing the water in the sediment of those objects was included. Releases were assumed to take place to these compartments. The modified module version is described in Appendix 4.

For this modified module, some additional parameters were required, in particular the fraction of the sediment area in which sedimentation processes occur. This value was selected as 0.99 in order to represent a large difference to the original module. This parameter would have to be investigated in more detail if a relevant influence from this module modification was found.

It can be seen that the effects are generally larger for the mean of the total dose, while for the maximum of the total dose the differences are almost non-existing (table 37). The exception to this is Am-241 with a relative difference larger than a factor of 2 for the maximum of the total dose. These results arise from the fact that the maximum of the total dose is determined by the object with the maximum dose contributions. This is in all cases except Am-241 a forest object for which the change in the input location does not have an effect.

Since the maximum landscape dose conversion factor eventually will be more important, it can be concluded from this variant calculation that the effect of the location of the input in current type of modules will only require further attention if doses from Am-241 play a relevant role. This can be assessed based on the landscape dose conversion factor and the actual source term for this radionuclide. It should also be considered in this respect that the parameters chosen for this variant calculation would require to be revised if the module modification is to be used, which might lead to a smaller difference to the original model.

Table 37. *Comparison of releases to lakes and coast objects through sediments and directly to water.*

Nuclide	Maximum total dose (DTotMax)			Mean total dose (DTotMean)		
	Sediment	**To water**	**Ratio**	**Sediment**	**To water**	**Ratio**
Cl-36	1.02E-13	1.02E-13	1	1.69E-16	1.72E-16	0.98
Tc-99	3.98E-15	3.98E-15	1	1.04E-17	1.10E-17	0.95
I-129	4.03E-12	4.03E-12	1	9.77E-15	1.25E-14	0.78
Ni-59	2.21E-14	2.21E-14	1	2.96E-17	3.12E-17	0.95
Pu-239	1.17E-13	1.17E-13	1	4.33E-14	4.54E-14	0.95
Cs-135	1.69E-11	1.69E-11	1	2.31E-14	2.70E-14	0.86
Se-79	1.37E-12	1.37E-12	1	2.03E-15	3.28E-15	0.62
Am-241	1.12E-14	2.74E-14	0.41	4.25E-15	5.82E-15	0.73
Th-230	4.15E-13	4.15E-13	1	4.76E-14	5.25E-14	0.91
Ra-226	1.74E-10	1.74E-10	1	2.29E-13	2.35E-13	0.98

In conclusion, the simpler (and conservative) model which disregards the effect of sediments should be used, unless a major dose contribution from Am-241 (or other radionuclides with similar behaviour) is envisaged or the mean landscape doses play more significant role in the assessment. In this case, modelling of the input location should be investigated more deeply.

Another situation in which a more detailed investigation of this issue would be warranted arises if changes of models and/or data result in other objects than forest becoming dominating. The modelling of sediments would also be relevant if changes of landscapes driven by land uplift can lead to former lake or coast sediments being transformed into agricultural land. Such effects will have to be addressed by dynamic modelling of landscape development.

6.4.3 Accumulation time

In this variant calculation, the time to reach equilibrium was studied. The simulations were performed for the unit release using the same data as for the central case. The model simulated a period of 1 million years to allow adequate time for all radionuclides. The time needed to reach 90 and 95 % of the maximum value were taken as indicators for the time to reach equilibrium.

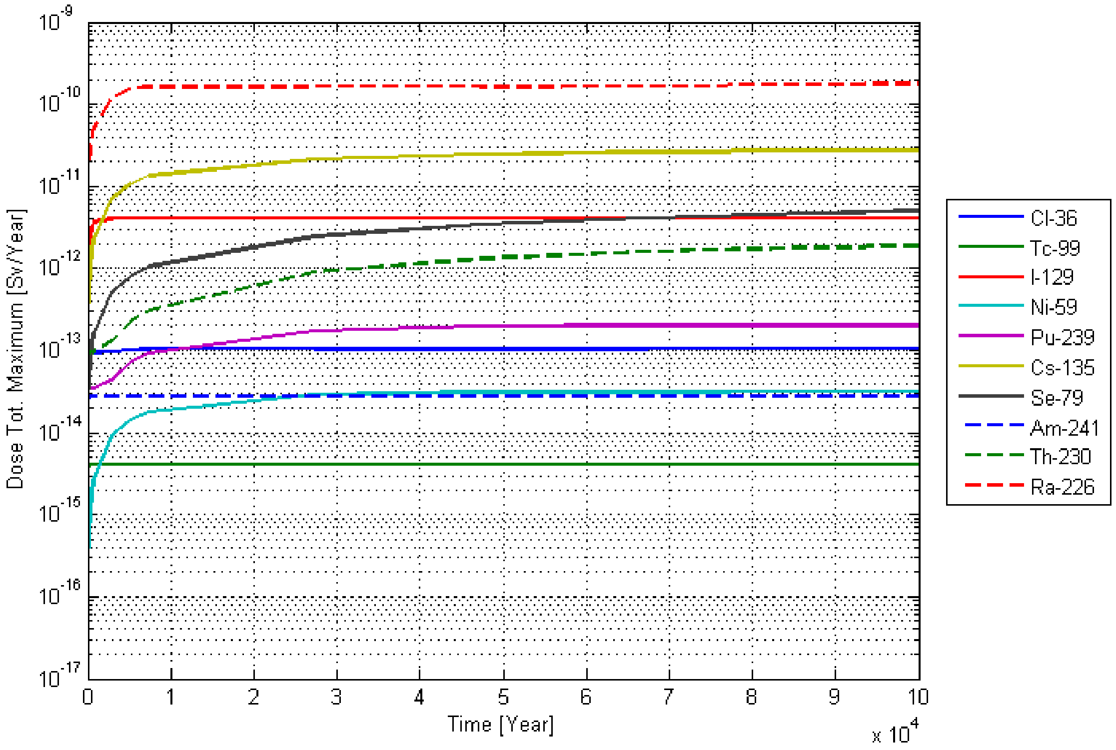


Figure 28. *Maximum total landscape doses from a long-term simulation based on the central case data, to study the time required to reach equilibrium for each radionuclide.*

Table 38. *Time (years) required to reach 90% and 95% of the maximum of the maximum total landscape dose (DTotMax) for each radionuclide using the landscape of young inland site.*

Nuclide	**90%**	**95%**
Cl-36	315	420
Tc-99	210	314
I-129	420	630
Ni-59	1.04E+04	1.34E+04
Pu-239	1.67E+04	2.17E+04
Cs-135	1.20E+04	1.54E+04
Se-79	3.70E+04	4.84E+04
Am-241	31	42
Th-230	7.17E+04	9.34E+04
Ra-226	5.05E+03	6.72E+03

It can be seen that the radionuclides taking the longest time to reach equilibrium are Th-230 and Se-79 with low mobility and relatively long half-lives. Based on the time to reach 95% of the maximum of the maximum of the total dose, the longest time to reach equilibrium for any of the included radionuclides is about 100,000 years for Th-230. All other radionuclides, except Se-79, require a much shorter time period.

These results provide an illustration of the overall model dynamics. They should not be used for practical purposes because they do not take into account that the landscape will evolve with time over much shorter time-scales than the times presented for many of the radionuclides in Table 37. In such cases the model will have to be modified to consider these changes and the equilibrium times from Table 37 will no longer be valid. More detailed assessments are required taking these aspects into account for deriving results which can be applied in practice.

7 CONCLUSIONS AND RECOMMENDATIONS

This report documents the landscape modelling cases implemented in the fall of 2005, complemented in 2006. This represents an approach for estimating doses to inhabitants of a landscape consisting of several interacting ecosystems which are affected by the contamination from potential radionuclide releases from a deep geological repository. From the model outputs, Landscape Dose Conversion Factors are calculated. These represent, for each radionuclide of concern, an estimate of the dose arising from a unit release of activity into the landscape objects. Modelling is undertaken for static landscapes corresponding to future landscape configurations expected for four different points in time.

The results presented are not yet suitable for practical application to estimate doses which could result from the planned repository at the Olkiluoto site. To suit this eventual purpose, refinements of the modelling and in the use of input parameter data will be necessary. The current report intends rather to investigate the important factors for potential future doses arising from the planned repository and to clarify methodological aspects. The results of this analysis are intended to serve as a basis for future assessments using improved input parameter data and improved models.

Notwithstanding the restrictions of the current modelling, important conclusions already can be drawn from the results presented in this report. Some of these will require to be reviewed based on results obtained with improved models and data. In particular, it will have to be investigated what effect a dynamic change of the landscape as opposed to the static consideration in this report has on the derived conclusions. Despite this necessity for review, it is believed that the conclusions presented below will remain valid in general.

The variation of the dose conversion factors calculated for different landscape configurations amounts to less than an order of magnitude. The important conclusion to be drawn from this result is that assumptions for future landscape development will only affect the predicted doses to a moderate extent. This finding is important for the building of confidence into the safety case by demonstrating that predicted doses do not drastically depend on models and assumptions for landscape development, which will always have considerable uncertainties. Nevertheless, there are relevant qualitative differences between the results for different landscape configurations. Thus, their consideration comprises an important element in the derivation of quantitative predictions.

The relative importance of different radionuclides does not change significantly between different landscape configurations. Therefore, the landscape model combined with estimates of the source term will provide a reliable basis for determining which radionuclides are of concern with regard to future exposures.

In all landscape configurations, forests are dominating the dose contributions for most radionuclides. This finding should be considered in the programme for further data acquisition and improvements of models.

For Am-241, Pu-239 and Th-230, the transfer of radionuclides to biota is of lesser importance than for the other radionuclides. Instead, the direct ingestion of drinking water is more relevant and, consequently, lake and river objects are of higher relative importance compared to the forest objects.

For mobile radionuclides such as iodine and technetium, equilibrium of the concentrations and resulting doses over time is achieved very fast. For less mobile elements, they increase over a period of a few thousand years and reach their equilibrium values then. Significant increases with time beyond this period only occur for a few radionuclides up to the order of 100,000 years for Th-230. However, these results should not be used for practical purposes because they do not take into account that the landscape will evolve with time over much shorter time-scales than the estimated time scales for reaching equilibrium. To adequately address this issue and identify its significance, a dynamic modelling of the landscape development is required.

The fraction of the total release retained in the system depends on mobility and half-life. Mobile elements such as chlorine, iodine and technetium are released for all landscape configurations relatively fast into the Baltic Sea. For less mobile radionuclides such as Am-241 and Ra-226, the dominating losses from the system occur through radioactive decay. Long-lived radionuclides with relatively low mobility such as Th-230 and Se-79 are retained in the system to a large extent. Only for these radionuclides, accumulation plays a major role as can be seen from the development of concentrations and doses with time.

The sensitivity analysis revealed that parameter values for transpiration, interception, soil distribution coefficients (Kd), as well as areas and catchment areas of the forest objects are of particular importance. This conclusion holds in general for all landscape configurations, although the details of the sensitivity results vary to some extent due to the different composition of objects in the four calculation cases. In addition, there is some dependency on the radionuclide considered. Based on estimates of the source term, these results should be used to direct future efforts for further developing models and acquiring data. For important parameters concerning future developments, which cannot be measured directly, adequate measures should be taken to reduce uncertainties and increase confidence (e.g. modelling, expert judgement).

The variant calculations for different release points show that differences are of an order of magnitude or less. A conservative model, assuming all releases to one object, therefore, would overestimate doses by one order of magnitude at maximum. Nevertheless, this overestimation should be avoided by assessing the discharge locations as good as possible. The results in this report can be used as guidance in this regard to determine which potential discharge locations have to be seen as particularly important.

Another variant calculation investigated the effect of changing the source term input location for lakes and rivers such that a layer of sediments at the bottom of the lake or river was considered. This resulted not (with the exception of Am-241) in changes of the maximum landscape dose in general dominated by forest objects. The average dose, however, which also has contributions from the other river and lake objects, was affected by a factor up to about two. Since the maximum landscape dose conversion factor eventually will be more important, it can be concluded from this variant calculation that the effect of the location of the input in current type of modules will only require further attention if doses from Am-241 play a relevant role. If this is not the case, in principle the simpler (and conservative) model disregarding the effect of sediments could be used. Another situation in which a more detailed investigation of this issue would be warranted arises if changes of models and/or data result in other objects than forest becoming dominating. The modelling of sediments would also be relevant if changes of landscapes driven by land uplift can lead to former lake or coast sediments being transformed into agricultural land.

Following these conclusions, it can be summarised that the future work should be focussed on the following aspects:

- The consequences from a dynamic modelling of the landscape development should be investigated. It should be established whether a static approach as presented in the current report using a representative landscape configuration is sufficient to derive reliable landscape dose conversion factors or whether effects caused by the landscape dynamics have such important consequences that their consideration is necessary in order to avoid overly conservative assumptions for a bounding static landscape. Amongst the dynamic effects to be studied should also be the relevance of the geosphere-biosphere interface in a dynamically developing landscape.
- The biosphere object modules and parameter values found important based on the results of these modelling cases should be reviewed and, to the extent practicable, improved.
- The conclusions above need to be reviewed based on improved modelling results.
- The importance of considering decay chains should be addressed with particular emphasis on considering the effect of short-lived daughter nuclides (e.g. Ra-226 daughters).

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APPENDIX A: INPUT PARAMETERS

The parameters of the landscape model were divided into three types: radionuclide specific (for example the distribution coefficients (Kd) and the soil-to-plant concentration ratios CR), object specific and system specific. Object specific parameters are parameters that have specific values for each particular object, such as the mean depth of a lake. System specific parameters are parameters that have the same value for all objects of the same type.

In table A-1 the parameters common for all models are presented, in table A-2 the radionuclide specific parameters are presented, and in tables A-3…A-5 the parameters with unique values for a specific landscape scenario are listed. The tables show a description of the parameter, the name in the model, the unit, the probability density function (PDF), and the reference. Some parameters listed here also occur for several of the scenarios but with different values due to changes in the landscape because of the land uplift. Whenever a minimum or maximum value is not shown the parameter in question was not varied during the sensitivity analysis, i.e. the parameter was held constant at its best estimate for all simulations. The site-specific parameters for which no reference is given are calculated from the terrain forecasts discussed in Section 3.1.

Table A-1. *System-specific parameter values applied.*

Parameter	**Name in model**	**Ecosystem**	**Best estimate**	**Min**	**Max**	**Unit**	**Reference**
Sediment density in wetlands	rho_peat	W	1100	700	1500	kg/m^3	Bergström et al. 1999
Sediment density in rivers (value for peat used)	rho_sed	R	1100	700	1500	kg/m^3	Bergström et al. 1999
Dry mass of surface sediment	rho_sed_Sea	C	10	5	15	kg/m^2	Bergström et al. 1999
Volumetric water content in soil	theta	F	0.15	0.05	0.25	m^3/m^3	Avila 2006a
Cross-sectional angle	Alpha	R	1.3963	1.2	1.42	degrees	Jonsson & Elert 2006
Diffusion coefficient	D	R	0.0158	0.0079	0.0237	m^2/y	Jonsson & Elert 2006
Particle size distribution (50% percentile)	D_50	R	0.0007	0.0005	0.0009	m	Jonsson & Elert 2006
Particle size distribution (90% percentile)	D_90	R	0.0019	0.0017	0.0021	m	Jonsson & Elert 2006
Annual average flow rate of Eurajoki	Flowrate_Eurajoki	-	284000000	157788000	568036800	m^3/y	Posiva 2005, Haapanen 2005
Annual average flow rate of Lapinjoki	Flowrate_Lapinjoki	-	71000000	39447000	142009200	m^3/y	Posiva 2005, Haapanen 2005
Interception fraction	I	F	0.34	0.1	0.75	-	Avila 2006a
Yearly production of tree leaves	LP	F	0.08	0.05	1.7	kg/m^2/y dw	Avila 2006a
Plant biomass in river	M_biomass	R	5	4	6	kg/m^2 fw	Jonsson & Elert 2006
Precipitation rate	P	F	0.532	0.41	0.685	m/y	Avila 2006a
Resuspension of surface sediment	Resusp	C	0.2	0.1	0.3	1/y	Bergström et al. 1999
Specific density	S	R	2.6	2.4	3.8	-	Jonsson & Elert 2006
Gross sedimentation rate	SR_Lake	L	1.1	0.5	1.5	kg/m^2/y dw	Vieno & Suolanen 1991
Gross sedimentation rate	SR_Sea	C	0.2	0.05	0.4	kg/m^2/y dw	Bergström et al. 1999
Suspended matter	Susp_Lake	L	0.005	0.005	0.06	kg/m^3 dw	Vieno & Suolanen 1991
Suspended matter	Susp_Sea	C	0.001	0.0005	0.002	kg/m^3 dw	Bergström et al. 1999
Transpiration	T	F	0.335	0.151	0.455	m/y	Avila 2006a
Tree lifetime	Tlife	F	100	70	200	y	Avila 2006a
Yearly production of understorey plants	UP	F	0.08	0.02	0.25	kg/m^2/y dw	Avila 2006a
Sedimentation velocity in rivers	V_partsed	R	400	300	500	m/y	Jonsson & Elert 2006

***Table A-1** (cont'd). System-specific parameter values applied.*

Parameter	**Name in model**	**Ecosystem**	**Best estimate**	**Min**	**Max**	**Unit**	**Reference**
Advective transport velocity in bed sediment	Vz	R	315.36	157.68	473.04	m/y	Jonsson & Elert 2006
Yearly production of tree wood	WP	F	0.18	0.018	1.8	kg/m^2/y dw	Avila 2006a
Suspended particulate matter in stream water	cp	R	0.02	0.01	0.03	kg/m^3	Jonsson & Elert 2006
Depth of surface sediment	deltaz1	R	0.5	0.25	0.75	m	Jonsson & Elert 2006
Depth of deep sediment	deltaz2	R	0.5	0.25	0.75	m	Jonsson & Elert 2006
Bulk density of forest soil	density_soil	F	1200	700	1500	kg/m^3	Avila 2006a
Thickness of soil rooting layer	h	F	0.24	0.1	0.4	m	Avila 2006a
Sediment porosity in wetlands	porosity_peat	W	0.8	0.7	0.9	m^3/m^3	Bergström et al. 1999
Sediment porosity in rivers	porosity_sed	R	0.8	0.7	0.9	-	Jonsson & Elert 2006
Production rate of carbon	pty_Forest	F	0.00026189			kg$_C$/m^2/y	SKB 2006
Production rate of carbon	pty_Lake	L	0.0039558			kg$_C$/m^2/y	SKB 2006
Production rate of carbon	pty_Mire	W	0.00019273			kg$_C$/m^2/y	SKB 2006
Production rate of carbon	pty_Sea	S	0.0053358			kg$_C$/m^2/y	SKB 2006
Production rate of carbon	pty_runwat	R	0.0039558			kg$_C$/m^2/y	SKB 2006
Concentration of particles in air	DustConc	-	5.00E-08			kg/m^3	Bergström et al. 1999
Exposure time to contaminated air	ExposureTime	-	8760			h/y	Bergström et al. 1999
Yearly intake of carbon by an individual	IRcarbon	-	110			kg$_C$/y	ICRP 1975
Yearly intake of water by an individual	IRwater	-	0.6			m^3/y	ICRP 1975, 2004
Inhalation rate by an individual	InhalationRate	-	1			m^3/h	ICRP 1975, 2004
Yearly fractional loss of litter biomass	TC_LitoS	-	0.16			1/y	Avila 2006a
Yearly fractional loss of tree leaves biomass	TC_LtoLi	-	0.25			1/y	Avila 2006a
Yearly fractional loss of understorey plants biomass	TC_UtoLi	-	1			1/y	Avila 2006a
Yearly fractional loss of tree wood biomass	TC_WtoLi	-	0.004			1/y	Avila 2006a
Half-time to reach sorption equilibrium	Tk	-	0.001			y	Jonsson & Elert 2006

Table A-2. *Radionuclide-specific parameter values applied.*

Parameter	**Name in model**	**Best estimate**	**Min**	**Max**	**Distribution**	**Unit**	**Reference**
Bioaccumulation factor sea water	BFcoast[Cl-36]	0.00726				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Tc-99]	0.218				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[I-129]	0.218				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Ni-59]	2.18				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Pu-239]	0.231				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Cs-135]	1.45				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Se-79]	29				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Am-241]	0.726				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Th-230]	0.218				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Ra-226]	0.363				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Pb-210]	0.726				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFcoast[Po-210]	14.5				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
Bioaccumulation factor lake water	BFlake[Cl-36]	0.363				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Tc-99]	0.145				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[I-129]	1.45				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Ni-59]	0.726				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Pu-239]	0.218				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Cs-135]	72.6				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Se-79]	14.5				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Am-241]	0.218				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Th-230]	0.726				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Ra-226]	0.363				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Pb-210]	2.18				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
	BFlake[Po-210]	0.363				$(Bq/kg_C) / (Bq/m^3)$	Karlsson & Bergström 2002
Concentration ratio from soil to tree leaves	CR_L[Cl-36]	10	0.09	0.23	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Tc-99]	1	2.36E-06	1.378E-4	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[I-129]	0.6	0.8	14	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a

Table A-2 (cont'd). Radionuclide-specific parameter values applied.

Parameter	Name in model	Best estimate	Min	Max	Distribution	Unit	Reference
Concentration ratio from soil to tree leaves	CR_L[Ni-59]	0.13	1.0259	59.9146	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Pu-239]	4.60E-05	6.67E-05	0.0038945	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Cs-135]	3.4	0.001	0.017	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Se-79]	20	3	170	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Am-241]	0.0013	0.5	20	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Th-230]	0.09	0.001	1.5	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Ra-226]	2.7	0.13849	8.0885	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Pb-210]	0.001	5.13E-05	0.0029957	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_L[Po-210]	0.05	0.0025647	0.14979	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
Concentration ratio from soil to understorey	CR_U[Cl-36]	28	0.01	4.7	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Tc-99]	1	5.00E-05	0.05	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[I-129]	0.6	0.1	100	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Ni-59]	0.13	1.0259	59.9146	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Pu-239]	0.002	1.50E-07	0.77	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Cs-135]	7	0.003	0.2	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Se-79]	20	0.8	11	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Am-241]	0.0013	0.0051293	0.29957	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Th-230]	0.09	0.0030776	0.17974	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Ra-226]	2.7	0.6	7.6	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Pb-210]	0.001	5.13E-05	0.0029957	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_U[Po-210]	0.05	0.0025647	0.14979	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
Concentration ratio from soil to tree wood	CR_W[Cl-36]	3	0.00066681	0.038945	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_W[Tc-99]	0.1	2.36E-06	0.0001378	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_W[I-129]	0.06	0.1	5.8	triangular	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_W[Ni-59]	0.013	0.10259	5.9915	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a
	CR_W[Pu-239]	4.60E-05	6.67E-06	3.8945E-04	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006a

Table A-2 *(cont'd). Radionuclide-specific parameter values applied.*

Parameter	**Name in model**	**Best estimate**	**Min**	**Max**	**Distribution**	**Unit**	**Reference**
Concentration ratio from soil to tree wood	CR_W[Cs-135]	0.8	0.00046164	0.026962	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
	CR_W[Se-79]	2	0.10259	5.9915	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
	CR_W[Am-241]	0.00013	6.67E-06	0.00038945	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
	CR_W[Th-230]	0.009	0.00046164	0.026962	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
	CR_W[Ra-226]	0.27	0.013849	0.80885	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
	CR_W[Pb-210]	0.0001	5.13E-06	0.00029957	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
	CR_W[Po-210]	0.005	0.00025647	0.014979	exp	(Bq/kg) / (Bq/kg) dw	Avila 2006
Aggregated transfer factor for forest	CRforest[Cl-36]	35.8364				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Tc-99]	6.5337				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[I-129]	4.0029				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Ni-59]	1.7708				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Pu-239]	0.00010385				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Cs-135]	54.5201				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Se-79]	3.1257				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Am-241]	0.00011071				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Th-230]	0.0043935				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Ra-226]	7.3623				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Pb-210]	0.010419				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
	CRforest[Po-210]	0.52095				(Bq/kg$_C$) / (Bq/kg)	Avila 2006b
Dose conversion coefficient from external exposure	DCCext[Cl-36]	0				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Tc-99]	0				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[I-129]	3.40E-16				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Ni-59]	0				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Pu-239]	6.60E-18				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Cs-135]	0				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Se-79]	0				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Am-241]	1.10E-15				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002

***Table A-2** (cont'd). Radionuclide-specific parameter values applied.*

Parameter	Name in model	Best estimate	Min	Max	Distribution	Unit	Reference
Dose conversion coefficient from external exposure	DCCext[Th-230]	3.50E-17				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Ra-226]	6.00E-16				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Pb-210]	7.20E-17				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
	DCCext[Po-210]	0				(Sv/h)/(Bq/m^3)	Karlsson & Bergström 2002
Dose conversion coefficient from food ingestion	DCCing[Cl-36]	9.30E-10				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Tc-99]	6.40E-10				Sv/Bq	Karlsson & Bergström 2002
	DCCing[I-129]	1.10E-07				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Ni-59]	6.30E-11				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Pu-239]	2.50E-07				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Cs-135]	2.00E-09				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Se-79]	2.90E-09				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Am-241]	2.00E-07				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Th-230]	2.10E-07				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Ra-226]	2.80E-07				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Pb-210]	6.90E-07				Sv/Bq	Karlsson & Bergström 2002
	DCCing[Po-210]	1.20E-06				Sv/Bq	Karlsson & Bergström 2002
Dose conversion coefficient from inhalation	DCCinh[Cl-36]	7.30E-09				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Tc-99]	1.30E-08				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[I-129]	3.60E-08				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Ni-59]	4.40E-10				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Pu-239]	0.00012				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Cs-135]	8.60E-09				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Se-79]	6.80E-09				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Am-241]	9.60E-05				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Th-230]	0.0001				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Ra-226]	9.50E-06				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Pb-210]	5.60E-06				Sv/Bq	Karlsson & Bergström 2002
	DCCinh[Po-210]	4.30E-06				Sv/Bq	Karlsson & Bergström 2002

***Table A-2** (cont'd). Radionuclide-specific parameter values applied.*

Parameter	Name in model	Best estimate	Min	Max	Distribution	Unit	Reference
Distribution coefficient for sea	Kd_Sea[Cl-36]	0.001	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Tc-99]	0.1	10	1000	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[I-129]	0.3	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Ni-59]	10	1	10	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Pu-239]	100	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Cs-135]	10	10	1000	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Se-79]	5	0.0001	0.01	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Am-241]	10	0.01	1	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Th-230]	100	0.1	1	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Ra-226]	10	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Pb-210]	0.05	0.01	0.1	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_Sea[Po-210]	20000	100	50000	logtriangular	m³/kg	Karlsson & Bergström 2002
Distribution coefficient for lake	Kd_lake[Cl-36]	0.001	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Tc-99]	0.1	10	1000	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[I-129]	0.3	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Ni-59]	10	1	10	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Pu-239]	100	0.5	50	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Cs-135]	10	10	1000	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Se-79]	5	0.001	0.1	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Am-241]	5	4.00E-05	0.06	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Th-230]	100	0.003	0.3	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Ra-226]	10	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Pb-210]	0.05	1.00E-02	0.1	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_lake[Po-210]	10	1	100	logtriangular	m³/kg	Karlsson & Bergström 2002
Distribution coefficient for peat	Kd_peat[Cl-36]	0.01	0.2	7	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Tc-99]	0.002	0.2	20	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[I-129]	0.03	0.1	3	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Ni-59]	1	0.2	20	logtriangular	m³/kg	Karlsson & Bergström 2002

***Table A-2** (cont'd). Radionuclide-specific parameter values applied.*

Parameter	Name in model	Best estimate	Min	Max	Distribution	Unit	Reference
Distribution coefficient for peat	Kd_peat[Pu-239]	2	10	1000	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Cs-135]	0.3	9	900	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Se-79]	2	0.001	0.1	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Am-241]	100	4.50E-05	0.07	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Th-230]	90	0.0008	0.3	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Ra-226]	2	0.2	20	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Pb-210]	20	8.00E+00	60	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_peat[Po-210]	7	0.7	700	logtriangular	m³/kg	Karlsson & Bergström 2002
Distribution coefficient for forest soil	Kd_peat[Cl-36]	0.01	0.2	7	logtriangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Tc-99]	0.003	0.2	200	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[I-129]	0.03	0.4	53	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Ni-59]	1	0.2	7	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Pu-239]	2	10	1000	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Cs-135]	0.8	1	100	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Se-79]	2	0.10259	5.9915	exp	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Am-241]	100	10	1000	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Th-230]	10	1	100	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Ra-226]	2	0.2	20	triangular	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Pb-210]	20	1.0259	59.9146	exp	m³/kg	Karlsson & Bergström 2002
	Kd_soil[Po-210]	7	0.35905	20.9701	exp	m³/kg	Karlsson & Bergström 2002

Table A-3. *Site-specific parameter values applied for the present landscape.*

Parameter	Name in model	Best estimate	Min	Max	Unit	Reference
Area of Baltic Sea volume	BalticSea.area	3.77E+11			m²	Seifert et al. 2001
Area of northern forest	ForestNorth.Area	1000000	502000	3050000	m²	
Area of southern forest	ForestSouth.Area	1230000	617000	1850000	m²	
Area of inner coast 1	InnerCoast1.area	10600000	5310000	15900000	m²	
Area of inner coast 2	InnerCoast2.area	5080000	2540000	7620000	m²	
Area of inner coast 3	InnerCoast3.area	14800000	7390000	22200000	m²	
Area of outer coast	OuterCoast.area	100000000	80000000	120000000	m²	
Cathment area of northern forest	ForestNorth.CatchmentArea	3050000	251000	4790000	m²	
Catchment area of southern forest	ForestSouth.CatchmentArea	1230000	308000	2910000	m²	
Average depth of Baltic Sea volume	BalticSea.D	106.5			m	Seifert et al. 2001
Average depth of inner coast 1	InnerCoast1.D	2.5	1	5	m	
Average depth of inner coast 2	InnerCoast2.D	4	2	15	m	
Average depth of inner coast 3	InnerCoast3.D	10	3	15	m	
Average depth of outer coast	OuterCoast.D	7	6	8	m	
Water retention time of the Baltic volume	BalticSea.RetTime	20			y	Bergström et al. 1999
Water retention time of outer coast	OuterCoast.retentionTime	0.02	0.0137	0.0274	y	Karlsson & Bergström 2000

Table A-4. *Site-specific parameter values applied for the landscape of first larger lakes.*

Parameter	Name in model	Best estimate	Min	Max	Unit	Reference
Area of Baltic Sea volume	BalticSea.area	3.77E+11			m^2	Seifert et al. 2001
Area of northern forest	ForestN.Area	2160000	502000	4430000	m^2	
Area of southern forest	ForestS.Area	1490000	617000	1850000	m^2	
Area of Inner coast 1	InnerCoast1.area	2620000	1310000	4110000	m^2	
Area of Inner coast 2	InnerCoast2.area	533000	267000	838000	m^2	
Area of Inner coast 3	InnerCoast3.area	891000	446000	1400000	m^2	
Area of Kiskarinjärvi	Kiskarinjärvi.Area	139000	111200	218000	m^2	
Area of Kornanjärvi	Kornanjärvi.Area	855000	257000	1340000	m^2	
Area of Liiklanjärvi	Liiklanjärvi.Area	413000	41300	650000	m^2	
Area of Liiklansuo	Liiklansuo.area	1630000	490000	1960000	m^2	
Area of Liponjärvi	Liponjärvi.Area	6940000	2080000	10900000	m^2	
Area of Liponsuo	Liponsuo.area	344000	86100	689000	m^2	
Area of Outer coast	OuterCoast.area	100000000	80000000	120000000	m^2	
Catchment area of northern forest	ForestN.CatchmentArea	4430000	251000	6970000	m^2	
Catchment area of southern forest	ForestS.CatchmentArea	1490000	308000	2910000	m^2	
Catchment area of Kiskarinjärvi	Kiskarinjärvi.CatchmentArea	873360	435000	1370000	m^2	
Catchment area of Kornanjärvi	Kornanjärvi.CatchmentArea	5372100	2690000	8440000	m^2	
Catchment area of Liiklanjärvi	Liiklanjärvi.CatchmentArea	206500	103000	325000	m^2	
Catchment area of Liiklansuo	Liiklansuo.CatchmentArea	3270000	1630000	5130000	m^2	
Catchment area of Liponjärvi	Liponjärvi.CatchmentArea	21803000	10900000	34200000	m^2	
Catchment area of Susijoki	Susijoki.CatchmentArea	2620000	1310000	4110000	m^2	
Average depth of Baltic Sea volume	BalticSea.D	106.5			m	Seifert et al. 2001
Average depth of Inner coast 1	InnerCoast1.D	0.8	0.5	3.6	m	
Average depth of Inner coast 2	InnerCoast2.D	1.5	0.5	2.5	m	
Average depth of Inner coast 3	InnerCoast3.D	1.5	0.5	2.5	m	
Average depth of Kiskarinjärvi	Kiskarinjärvi.D	0.3	0.1	0.6	m	
Average depth of Kornanjärvi	Kornanjärvi.D	0.3	0.1	0.9	m	

***Table A-4** (cont'd). Site-specific parameter values applied for the landscape of first larger lakes.*

Parameter	Name in model	Best estimate	Min	Max	Unit	Reference
Average depth of Liiklanjärvi	Liiklanjärvi.D	2.3	0.3	4.8	m	
Average depth of Liponjärvi	Liponjärvi.D	5.8	0.3	9.7	m	
Average depth of Outer coast	OuterCoast.D	7	6	8	m	
Average depth of Pätkä	Pätkä.Depth	0.3	0.1	1	m	
Average depth of Susijoki	Susijoki.Depth	0.3	0.1	1	m	
Water retention time of Baltic Sea	BalticSea.RetTime_Sea	22			y	Bergström et al. 1999
Water retention time of Inner coast 1	InnerCoast1.RetTime_Sea	0.002	0.0014	0.0027	y	Vieno & Suolanen 1991
Water retention time of Inner coast 2	InnerCoast2.RetTime_Sea	0.002	0.0014	0.0027	y	Vieno & Suolanen 1991
Water retention time of Inner coast 3	InnerCoast3.RetTime_Sea	0.002	0.0014	0.0027	y	Vieno & Suolanen 1991
Water retention time of Outer coast	OuterCoast.RetTime_Sea	0.02	0.0137	0.0274	y	Karlsson & Bergström 2000
Average depth of Liiklansuo	Liiklansuo.D_peat	5	0.3	6	m	
Average depth of Liponsuo	Liponsuo.D_peat	0.9	0.3	5	m	
Runoff	Liiklansuo.runoff	0.24	0.2	0.28	m/y	
Runoff	Liponsuo.runoff	0.24	0.2	0.28	m/y	
Length of Pätkä	Pätkä.deltax	409	100	1500	m	
Length of Susijoki	Susijoki.deltax	1666	66.6	2900	m	

***Table A-5.** Site-specific parameter values applied for the landscape of young inland site.*

Parameter	Name in model	Best estimate	Min	Max	Unit	Reference
Area of Baltic Sea volume	BalticSea.area	3.77E+11			m^2	Seifert et al. 2001
Area of northern forest	ForestN.Area	2160000	502000	4430000	m^2	
Area of southern forest	ForestS.Area	1490000	617000	1850000	m^2	
Area of inner coast 1	IC1.area	1220000	611000	1830000	m^2	
Area of inner coast 2	IC2.area	1810000	907000	2720000	m^2	
Area of inner coast 3	IC3.area	640000	320000	960000	m^2	

Table A-5 *(cont'd). Site-specific parameter values applied for the landscape of young inland site.*

Parameter	**Name in model**	**Best estimate**	**Min**	**Max**	**Unit**	**Reference**
Area of inner coast 4	IC4.area	984000	492000	1480000	m^2	
Area of inner coast 5	IC5.area	2160000	1080000	3240000	m^2	
Area of Kiskarinjärvi	Kiskarinjarvi.Area	140000	111200	218000	m^2	
Area of Kornanjärvi	Korjnanjarvi.Area	850000	257000	1340000	m^2	
Area of Liiklanjärvi	Liiklanjarvi.Area	410000	41300	650000	m^2	
Area of Liiklansuo	Liiklansuo.area	1630000	490000	1960000	m^2	
Area of Liponjärvi	Liponjarvi.Area	6940000	2080000	10900000	m^2	
Area of Liponsuo	Liponsuo.area	344000	86100	689000	m^2	
Area of Susijärvi	Susijarvi.Area	2600000	785000	4110000	m^2	
Area of outer coast	OuterCoast.area	100000000	80000000	120000000	m^2	
Catchment area of northern forest	ForestN.CatchmentArea	4430000	251000	6970000	m^2	
Catchment area of southern forest	ForestS.CatchmentArea	1490000	308000	2910000	m^2	
Catchment area Kiskarinjarvi	Acatch_Kiskarinjarvi	870000	435000	1370000	m^2	
Catchment area Kornanjarvi	Acatch_Kornanjarvi	5370000	2690000	8440000	m^2	
Catchment area Liiklanjarvi	Acatch_Liiklanjarvi	207000	103000	325000	m^2	
Catchment area Liiklansuo	Acatch_Liiklansuo	3270000	1630000	5130000	m^2	
Catchment area Liponjarvi	Acatch_Liponjarvi	21800000	10900000	34200000	m^2	
Catchment area Pitkajoki	Acatch_Pitkajoki	17600	8800	27600	m^2	
Catchment area Susijarvi	Acatch_Susijarvi	8210000	4110000	12900000	m^2	
Catchment area Susijoki	Acatch_Susijoki	2620000	1310000	4110000	m^2	
Average depth of Baltic sea	BalticSea.D	106.5			m	Seifert et al. 2001
Average depth of iner coast 1	IC1.D	3	1	5	m	
Average depth of inner coast 2	IC2.D	3	1	5	m	
Average depth of inner coast 3	IC3.D	3	1	5	m	
Average depth of inner coast 4	IC4.D	3	1	5	m	
Average depth of inner coast 5	IC5.D	6	1	10	m	
Average depth of Kiskarinjarvi	Kiskarinjarvi.D	0.35	0.1	0.6	m	

Table A-5 *(cont'd). Site-specific parameter values applied for the landscape of young inland site.*

Parameter	**Name in model**	**Best estimate**	**Min**	**Max**	**Unit**	**Reference**
Average depth of Kornanjarvi	Kornanjarvi.D	0.3	0.1	0.9	m	
Average depth of Liiklanjarvi	Liiklanjarvi.D	2.3	0.3	4.8	m	
Average depth of Liponjarvi	Liponjarvi.D	5.8	0.3	9.7	m	
Average depth of outer coast	OuterCoast.D	7	6	8	m	
Average depth of Pätkä	Patka.Depth	0.3	0.1	1	m	
Average depth of Pitkajoki	Pitkajoki.Depth	0.3	0.1	1	m	
Average depth of Susijarvi	Susijarvi.D	0.8	0.5	2.9	m	
Average depth of Susijoki	Susijoki.Depth	0.3	0.1	1	m	
Water retention time of baltic sea volume	BalticSea.RetTime_Sea	22			y	Bergström et al. 1999
Water retention time of inner caost 1	IC1.RetTime_Sea	0.002	0.0014	0.0041	y	Karlsson & Bergström 2000
Water retention time of inner coast 2	IC2.RetTime_Sea	0.002	0.0014	0.0041	y	Karlsson & Bergström 2000
Water retention time of inner coast 3	IC3.RetTime_Sea	0.002	0.0014	0.0041	y	Karlsson & Bergström 2000
Water retention time of inner coast 4	IC4.RetTime_Sea	0.002	0.0014	0.0041	y	Karlsson & Bergström 2000
Water retention time of inner coast 5	IC5.RetTime_Sea	0.002	0.0014	0.0041	y	Karlsson & Bergström 2000
Water retention time of outer coast	OuterCoast.RetTime_Sea	0.02	0.0137	0.0274	y	Karlsson & Bergström 2000
Depth of Liiklansuo	Liiklansuo.D_peat	5.3	0.45	6.45	m	
Depth of Liponsuo	Liponsuo.D_peat	1.2	1.05	5.45	m	
Runoff	Liiklansuo.runoff	0.24	0.2	0.28	m/y	
Runoff	Liponsuo.runoff	0.24	0.2	0.28	m/y	
Length of Pätkä	Patka.deltax	409	100	1500	m	
Length of Pitkajoki	Pitkajoki.deltax	250	50	300	m	
Length of Susijoki	Susijoki.deltax	1700	1300	2000	m	

***Table A-6.** Site-specific parameter values applied for the landscape of far future.*

Parameter	**Name in model**	**Best estimate**	**Min**	**Max**	**Unit**	**Reference**
Area of Baltic sea volume	BalticSea.area	3.77E+11			m^2	Seifert et al. 2001
Area of northern forest	ForestN.Area	2160000	502000	4430000	m^2	
Area of southern forest	ForestS.Area	1490000	617000	1850000	m^2	
Area of Kaunissuo	Kaunissuo.area	2400000	1920000	2880000	m^2	
Area of Kiskarinjärvi	Kiskarinjarvi.Area	139000	111200	218000	m^2	
Area of Kornanjärvi	Kornanjarvi.Area	855000	257000	1340000	m^2	
Area of Liiklanjärvi	Liiklanjarvi.Area	413000	41300	650000	m^2	
Area of Liiklansuo	Liiklansuo.area	1630000	490000	1960000	m^2	
Area of Liponjarvi	Liponjarvi.Area	6940000	2080000	10900000	m^2	
Area of Liponsuo	Liponsuo.area	344000	86100	689000	m^2	
Area of outer coast	OuterCoast.area	100000000	80000000	120000000	m^2	
Area of Susijärvi	Susijarvi.Area	2620000	785000	4110000	m^2	
Catchment area of northern forest	ForestN.CatchmentArea	4430000	251000	6970000	m^2	
Catchment area of southern forest	ForestS.CatchmentArea	1490000	308000	2910000	m^2	
Catchment area of Kaunisjoki	Acatch_Kaunisjoki	1080000	541000	1700000	m^2	
Catchment area of Kiskarinjärvi	Acatch_Kiskarinjarvi	870000	435000	1370000	m^2	
Catchment area of Kornanjärvi	Acatch_Kornanjarvi	5370000	2690000	8440000	m^2	
Catchment area of Liiklanjärvi	Acatch_Liiklanjarvi	207000	103000	325000	m^2	
Catchment area of Liiklansuo	Acatch_Liiklansuo	3270000	1630000	5130000	m^2	
Catchment area of Liponjärvi	Acatch_Liponjarvi	21800000	10900000	34200000	m^2	
Catchment area of Nimeton	Acatch_Nimeton	344000	172000	541000	m^2	
Catchment area of Pitkajoki	Acatch_Pitkajoki	17600	8800	27600	m^2	
Catchment area of Susijärvi	Acatch_Susijarvi	8210000	4110000	12900000	m^2	
Catchment area of Susijoki	Acatch_Susijoki	2620000	1310000	4110000	m^2	
Average depth of Baltic sea volume	BalticSea.D	106.5			m	Seifert et al. 2001
Average depth of Kaunisjoki	Kaunisjoki.Depth	0.3	0.1	1	m	
Average depth of Kiskarinjärvi	Kiskarinjarvi.D	0.2	0.1	0.3	m	

***Table A-6** (cont'd). Site-specific parameter values applied for the landscape of far future.*

Parameter	**Name in model**	**Best estimate**	**Min**	**Max**	**Unit**	**Reference**
Average depth of Kornanjärvi	Kornanjarvi.D	0.2	0.1	0.4	m	
Average depth of Liiklanjarvi	Liiklanjarvi.D	2	0.3	4.3	m	
Average depth of Liponjarvi	Liponjarvi.D	5.5	0.3	9.2	m	
Average depth of Nimeton	Nimeton.Depth	0.3	0.1	1	m	
Average depth of outer coast	OuterCoast.D	7	6	8	m	
Average depth of Pätkä	Patka.Depth	0.3	0.1	1	m	
Average depth of Pitkajoki	Pitkajoki.Depth	0.3	0.1	1	m	
Average depth of Susijärvi	Susijarvi.D	0.5	0.2	2.4	m	
Average depth of Susijoki	Susijoki.Depth	0.3	0.1	1	m	
Water retention time of baltic sea volume	BalticSea.RetTime_Sea	20			y	Bergström et al. 1999
Water retention time of outer coast	OuterCoast.RetTime_Sea	0.02	0.0137	0.0274	y	Karlsson & Bergström 2000
Average depth of Kaunissuo	Kaunissuo.D_peat	3.424	2.162	8.782	m	
Average depth of Liiklansuo	Liiklansuo.D_peat	7.524	1.562	9.782	m	
Average depth of Liponsuo	Liponsuo.D_peat	3.424	2.162	8.782	m	
Runoff	Kaunissuo.runoff	0.24	0.2	0.28	m/y	Bergström et al. 1999
Runoff	Liiklansuo.runoff	0.24	0.2	0.28	m/y	Bergström et al. 1999
Runoff	Liponsuo.runoff	0.24	0.2	0.28	m/y	Bergström et al. 1999
Length of Kaunisjoki	Kaunisjoki.deltax	1917	1500	2300	m	
Length of Nimeton	Nimeton.deltax	1974	1900	6200	m	
Length of Pätkä	Patka.deltax	409	100	1500	m	
Length of Pitkajoki	Pitkajoki.deltax	8500	6800	11600	m	
Length of Susijoki	Susijoki.deltax	1666	66	2900	m	

APPENDIX B: MATHEMATICAL DESCRIPTION OF BIOSPHERE OBJECT MODULES

In this appendix, short descriptions are given on the biosphere object modules used to calculate the radionuclide transport in the linked system of ecosystems in the landscape model. For more detailed descriptions, see the references mentioned below. The input parameter values applied are listed in Appendix A.

Coast module

The coast module applied is adopted without changes from (Karlsson & Bergström 2000). The structure of the module is presented in Figure B-1 and Tables B-1 and B-2 list its transfer equations and parameters, respectively.

Table B-1. *Equations used in the coast module (Karlsson & Bergström 2000). The transfer numbers refer to Figure B-1.*

Transfer nr.	Transfer coefficient (Bq/y)
1, 6	$\frac{\mathrm{Resusp}}{\rho_{sed}}$
2, 7	$\frac{Kd \cdot SR}{D \cdot (1 + Kd \cdot Susp)}$
3, 8	$\frac{\mathrm{SR} - \mathrm{Resusp}}{\rho_{sed}}$
4	$\frac{1}{\mathrm{Re\,tTime}}$
5	$\frac{1}{\mathrm{Re\,tTime}} \cdot \frac{V_{bay}}{V_{Sea}}$

Table B-2. *Parameters in the coast module (Karlsson & Bergström 2000).*

Parameter name	Description
Resusp	Resuspended fraction
ρ_{sed}	Mass of upper sediment
Kd	Distribution factor
SR	Gross sediment rate
D	Mean depth
Susp	Concentration of suspended matter in water
RetTime	Retention Time for inner coast water (bay)
V_{Sea}	Water volume of sea (outer coast)
V_{bay}	Water volume of bay (inner coast)

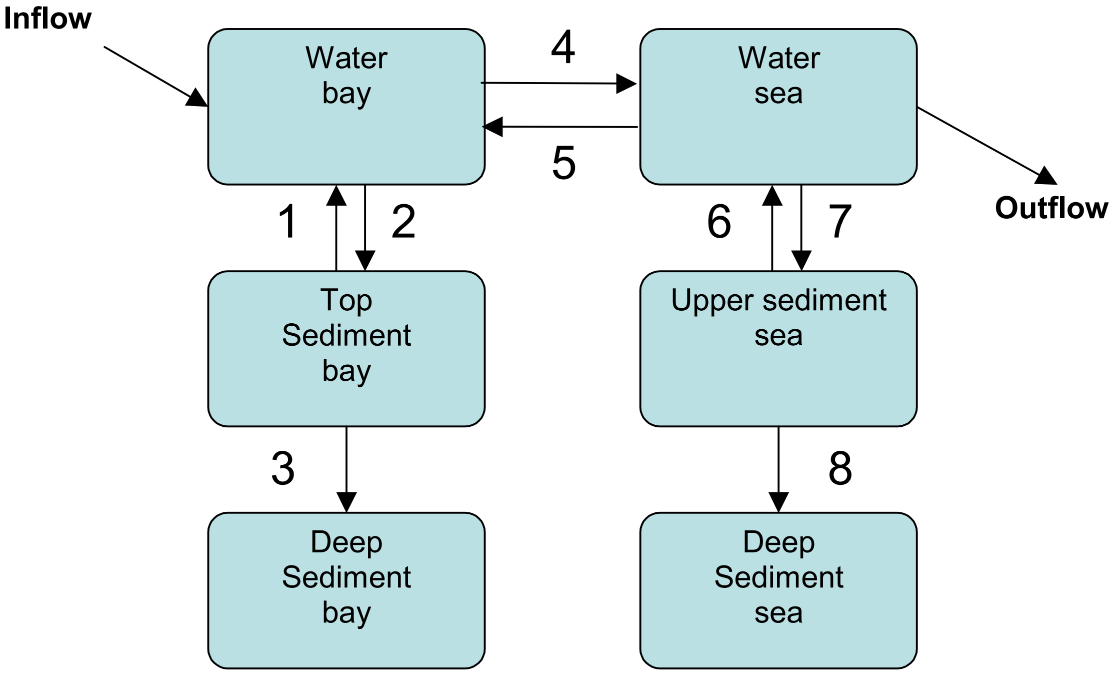

Figure B-1. *Module structure in the coast module (Karlsson & Bergström 2000). The transfer numbers refer to Table B-1.*

Lake module

The lake module applied is adopted without changes from (Karlsson & Bergstöm 2000). The structure of the module is presented in Figure B-2 and Tables B-3 and B-4 list its transfer equations and parameters, respectively.

Table B-3. *Equations used in the lake module (Karlsson & Bergström 2000). The transfer numbers refer to Figure B-2.*

Transfer nr.	Transfer coefficient (Bq/y)
1	$\frac{\mathrm{Resusp}}{\rho_{sed}}$
2	$\frac{Kd \cdot SR}{D \cdot (1 + Kd \cdot Susp)}$
3	$\frac{\mathrm{SR} - \mathrm{Resusp}}{\rho_{sed}}$
4	$\frac{1}{\mathrm{RetTime}}$

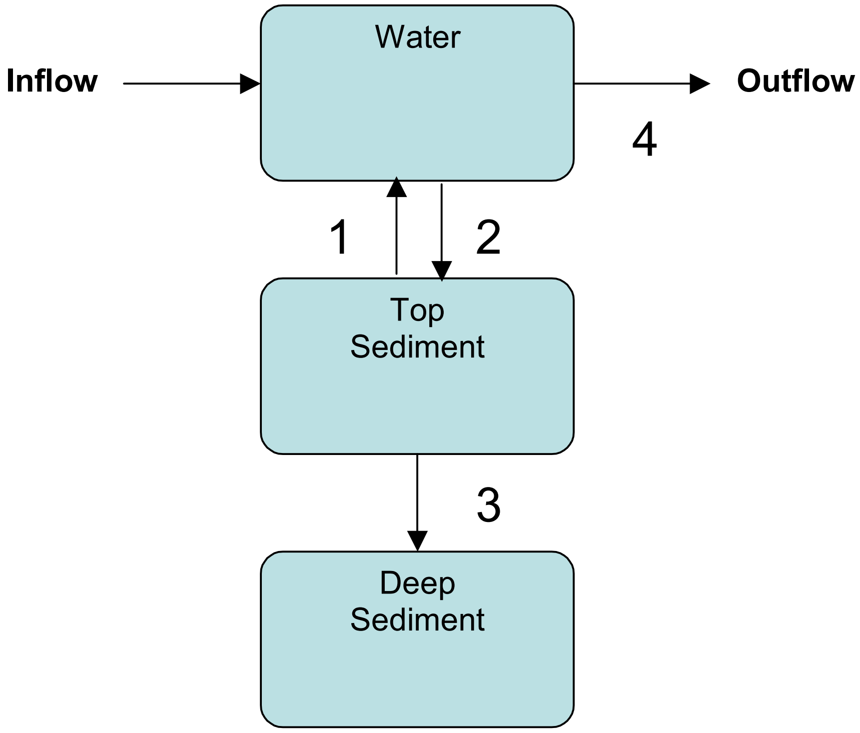

Figure B-2. *Module structure in the lake module (Karlsson & Bergström 2000). The transfer numbers refer to Table B-3.*

Table B-4. *Parameters in the lake module (Karlsson & Bergström 2000).*

Parameter name	**Description**
Resusp	Resuspended fraction
ρ_{sed}	Mass of upper sediment
Kd	Distribution factor
SR	Gross sedimentation rate
D	Mean depth
Susp	Concentration of suspended matter in water
RetTime	Retention time in lake

Wetland module

The wetland module applied is adopted without changes from (Karlsson & Bergstöm 2000). The structure of the module is presented in Figure B-3 and Tables B-5 and B-6 list its transfer equations and parameters, respectively.

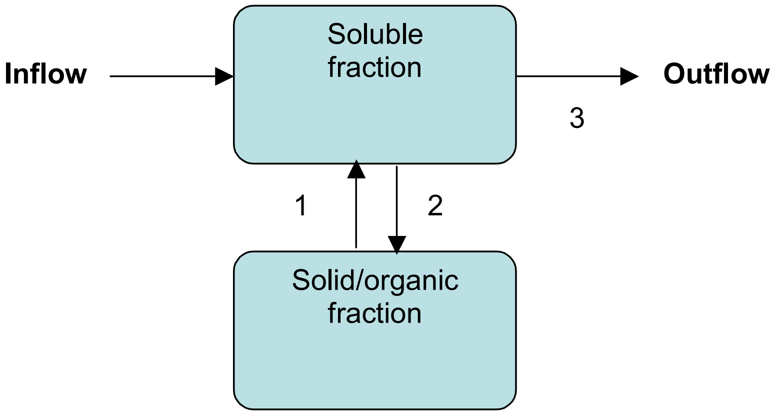

Figure B-3. *Module structure in the wetland module (Karlsson & Bergström 2000). The transfer numbers refer to Table B-5.*

Table B-5. *Equations used in the wetland module (Karlsson & Bergström 2000). The transfer numbers refer to Figure B-3.*

Transfer nr.	Transfer coefficient (Bq/y)
1	$\frac{\ln 2}{Tk}$
2	$\frac{Kd \cdot \ln 2 \cdot \rho_{peat}}{Tk \cdot \theta_{peat}}$
3	$\frac{\mathrm{R} \cdot \mathrm{A}}{\theta_{peat} \cdot D_{peat} \cdot A}$

Table B-6. *Parameters in the wetland module (Karlsson & Bergström 2000).*

Parameter name	Description
Kd	Distribution factor
ρ_{peat}	Density of peat sediment
Tk	Halftime to reach sorption equilibrium
θ_{peat}	Porosity of peat sediment
R	Runoff
A	Area of peat bog
D	Depth of peat bog

River module

The river module applied is adopted without changes from (Jonsson & Elert 2005). The structure of the module is presented in Figure B-4 and Tables B-7 and B-8 list its transfer equations and parameters, respectively.

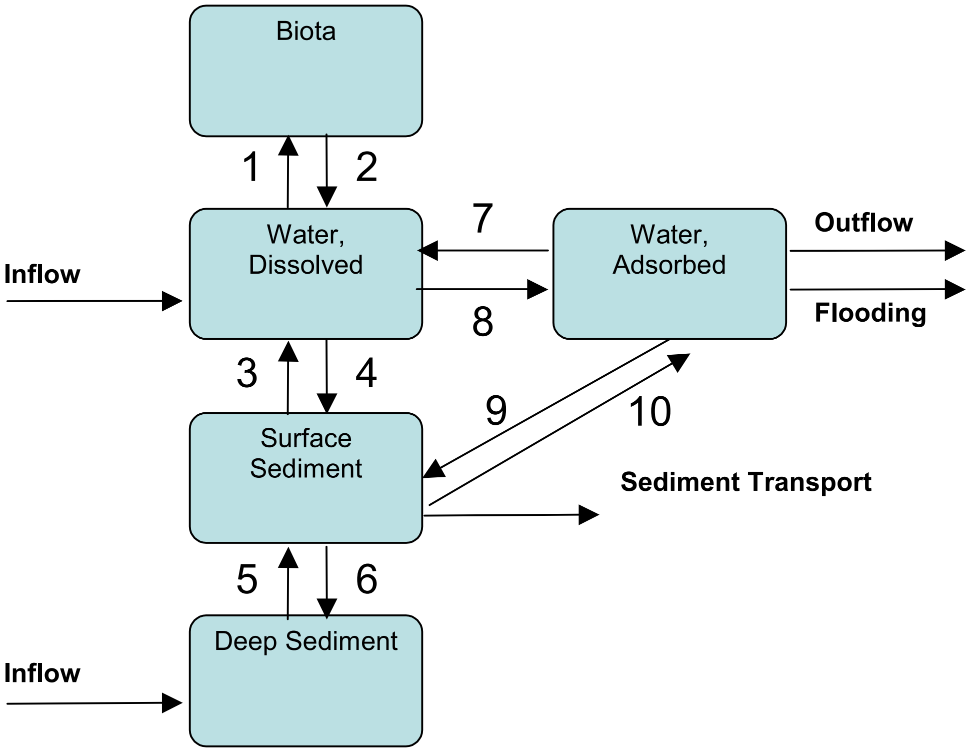

Figure B-4. Module structure in the river module (Jonsson & Elert 2005). The transfer numbers refer to Table B-7.

Table B-7. *Equations used in the river module (Jonsson & Elert 2005). The transfer numbers refer to Figure B-4.*

Transfer nr.	Transfer coefficient (Bq/y)
1	$BCF \frac{M_{biomass,\,tot}}{\forall_{water}} k_{biota}$
2	k_{biota}
3	$\frac{2D\eta P\Delta x}{\Delta z_1 (1 + K_B \rho_{sed}) \forall_{sed,1}} + \frac{V_z P\Delta x}{2\,(1 + K_B \rho_{sed}) \forall_{sed,1}}$
4	$\frac{2D\eta}{\Delta z_1 R_h} + \frac{V_z}{2R_h}$
5	$\frac{2D\eta A_{deep}}{\Delta z_2 (1 + K_B \rho_{sed}) \forall_{sed,2}} + \frac{V_z A_{deep}}{2\,(1 + K_B \rho_{sed}) \forall_{sed,2}}$
6	$\frac{2D\eta A_{deep}}{\Delta z_1 (1 + K_B \rho_{sed}) \forall_{sed,1}} + \frac{V_z A_{deep}}{2\,(1 + K_B \rho_{sed}) \forall_{sed,1}}$

Table B-*7 (cont'd). Equations used in the river module (Jonsson & Elert 2005). The transfer numbers refer to Figure B-4.*

Transfer nr.	Transfer coefficient (Bq/y)
7	$\frac{\ln(2)}{T_k c_p K_d}$
8	$\frac{\ln(2)}{T_k}$
9	$\frac{K_d c_p V_{partsed}}{(1 + K_d c_p) R_h}$
10	$\frac{\text{Resuspension } K_B}{(1 + K_B \rho_{sed}) \forall_{sed,1}}$
Outflow	$\frac{V_{adv}}{\Delta x}$
Sediment transport	$\frac{q_b w}{\forall_{sed,1} \left(1 + \frac{1}{\rho_{sed} K_B}\right)}$
Flooding	$\frac{q_{flooded\ water}}{\Delta x\ A_{cross}}$

Table B-8. *Parameters in the river module (Jonsson & Elert 2005).*

Parameter name	**Description**
K_d	Distribution coefficient in the stream water
K_B	Distribution coefficient in the sediment
T_k	Half-time to reach sorption equilibrium
BCF	Bioconcentration factor
q_s	Specific run-off
A_{ws}	Watershed area
α	Cross-sectional angle
S_b	Slope of the channel
Δx	Length of the channel
y_{max}	Maximum depth in main channel
ρ_{sed}	Sediment density
V_z	Advective transport velocity in bed sediment
D_{50}, D_{90}	Particle size distribution in the sediment
c_p	Suspended particulate matter in stream water
η	Sediment porosity
D	Diffusion coefficient
Δz_i	Depth of surface and deep sediment

Table B-8 *(cont'd). Parameters in the river module (Jonsson & Elert 2005).*

Parameter name	**Description**
$M_{biomass}$	Plant biomass
n	Manning friction coefficient
$\forall_{sed,1}$	Volume of upper sediment
$\forall_{sed,2}$	Volume of deep sediment
$\forall_{water}$	Volume of water
A_{cross}	Cross-sectional area of water stream
A_{deep}	Area of deep sediment (equal to area of upper sediment)
V_{adv}	Advective velocity
$Resuspension$	Resuspension factor
R_h	Hydraulic radius
$q_{flooded\ water}$	Yearly average of flooded water flowing out of water stream
$V_{partsed}$	Sedimentation velocity

Forest module

The forest module applied from (Avila 2006) is modified to distribute the input over the full forest area instead of calculating the activity per square meter as originally done. The structure of the module is presented in Figure B-5 and Tables B-9 and B-10 list its transfer equations and parameters, respectively.

Table B-9. *Equations used in the forest module modified from (Avila 2006). The transfer numbers refer to Figure B-5.*

Transfer nr.	**Transfer coefficient (Bq/y)**
1	$WP \cdot \frac{CR_W}{\rho \cdot h}$
2	$LP \cdot \frac{CR_L}{\rho \cdot h}$
3	$UP \cdot \frac{CR_U}{\rho \cdot h}$
4	TC_{LToLi}
5	TC_{WToLi}
6	TC_{UToLi}
Outflow	$\frac{P - ET}{h \cdot (\theta + Kd \cdot \rho)}$

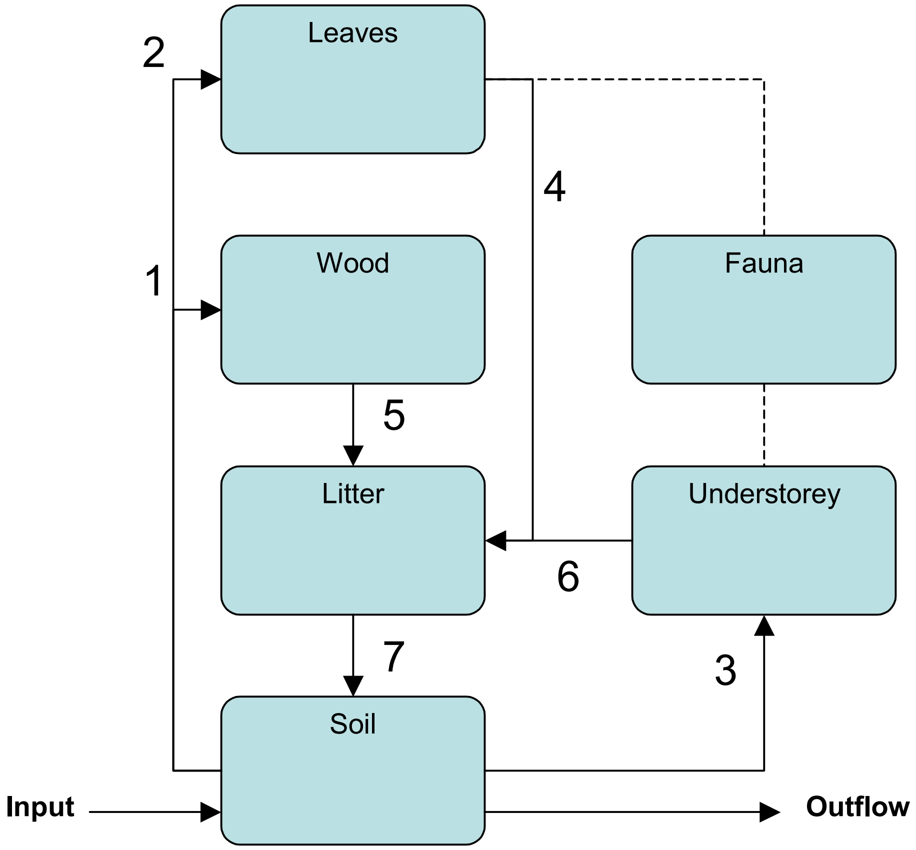

Figure B-5. *Module structure in the forest module modified from (Avila 2006). The transfer numbers refer to Table B-9.*

Table B-10. *Parameters in the forest module modified from (Avila 2006).*

Parameter name	**Description**
WP	Yearly production of tree wood
CR_W	Concentration ratio of nuclides from soil to tree wood
LP	Yearly production of tree leaves
CR_L	Concentration ratio of nuclides from soil to leaves
UP	Yearly production of understorey plants
CR_U	Concentration ratio of nuclides from soil to understorey plants
TC_{LToLi}	Yearly fractional loss of tree leaves biomass
TC_{WToLi}	Yearly fractional loss of tree wood biomass
TC_{UToLi}	Yearly fractional loss of understorey plants biomass
ρ	Soil bulk density
H	Thickness of the soil rooting layer
P	Precipitation rate
ET	Area normalised evapotranspiration rate
θ	Volumetric water content in soil
Kd	Distribution factor in soil

APPENDIX C: MODIFICATIONS OF COAST AND LAKE MODULES FOR VARIANT CASE STUDY

To study the effect of releases to the sediments, modified versions of the coast and lake models were used, similar to those in (SKB 2006). The changes applied were the same for both the coast and lake model and is illustrated in Figure C-1 and Tables C-1 and C-2 list its transfer equations and parameters, respectively.

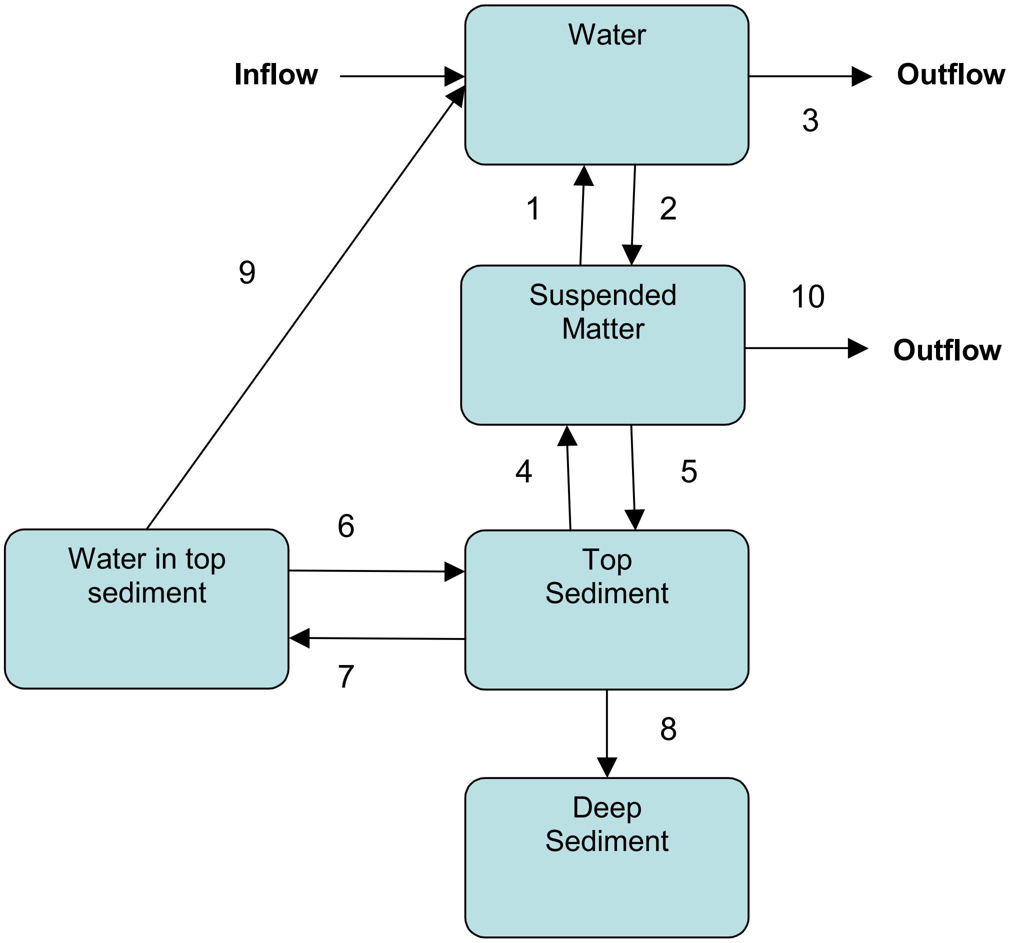

Figure C-1. *Structure of the modified coast and lake object modules (SKB 2006). The transfer numbers refer to Table C-1.*

Table C-1. *Equations used in the modified coast and lake object modules (SKB 2006). The transfer numbers refer to Figure C-1.*

Transfer nr.	Transfer coefficient (Bq/y)
1	$\frac{\ln(2)}{Tk}$
2	$\frac{\ln(2)}{Tk} \cdot Susp \cdot Kd$
3	$\frac{1}{RETTIME}$
4	$\frac{Gs}{Ds} \cdot (1 - FracX)$
5	$\frac{Vs}{D}$
6	$\frac{Kd \cdot \rho \cdot \log(2)}{\theta \cdot Tk}$
7	$\frac{\log(2)}{Tk}$
8	$\frac{Gs}{Ds} \cdot FracX$
9	$\frac{\log(2) \cdot Vadv}{Ds}$
10	$\frac{1}{RETTIME}$

Table C-2. *Parameters in the modified coast and lake object modules (SKB 2006).*

Parameter name	**Description**
Tk	Halftime to reach sorption equilibrium
Susp	Suspended matter
Kd	Distribution coefficient
RETTIME	Water retention time
Gs	Sediment growth rate
Ds	Depth of sediment
FracX	Fraction accumulation bottom
Vs	Fine particle settling velocity
D	Mean depth
ρ	Density of sediment
θ	Porosity of sediment
Vadv	Advection velocity in sediment