r

SSI report

SSI Rapport
2008:09

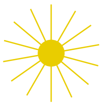
Rapport från Statens strålskyddsinstitut
tillgänglig i sin helhet via www.ssi.se

The Generalised Ecosystem Modelling Approach in Radiological Assessment

Richard Kłos

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

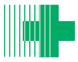
SSI's Activity Symbols



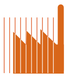
Ultraviolet, solar and optical radiation
Ultraviolet radiation from the sun and solariums can result in both long-term and short-term effects. Other types of optical radiation, primarily from lasers, can also be hazardous. SSI provides guidance and information.

Solariums
The risk of tanning in a solarium are probably the same as tanning in natural sunlight. Therefore SSI's regulations also provide advice for people tanning in solariums.

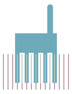
Radon
The largest contribution to the total radiation dose to the Swedish population comes from indoor air. SSI works with risk assessments, measurement techniques and advises other authorities.



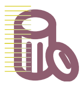
Health care
The second largest contribution to the total radiation dose to the Swedish population comes from health care. SSI is working to reduce the radiation dose to employees and patients through its regulations and its inspection activities.



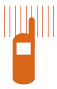
Radiation in industry and research
According to the Radiation Protection Act, a licence is required to conduct activities involving ionising radiation. SSI promulgates regulations and checks compliance with these regulations, conducts inspections and investigations and can stop hazardous activities.



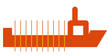
Nuclear power
SSI requires that nuclear power plants should have adequate radiation protection for the generalpublic, employees and the environment. SSI also checks compliance with these requirements on a continuous basis.



Waste
SSI works to ensure that all radioactive waste is managed in a manner that is safe from the standpoint of radiation protection.



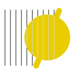
Mobile telephony
Mobile telephones and base stations emit electromagnetic fields. SSI is monitoring developments and research in mobile telephony and associated health risks.



Transport
SSI is involved in work in Sweden and abroad to ensure the safe transportation of radioactive substances used in the health care sector, industrial radiation sources and spent nuclear fuel.

Environment
"A safe radiation environment" is one of the 15 environmental quality objectives that the Swedish parliament has decided must be met in order to achieve an ecologically sustainable development in society. SSI is responsible for ensuring that this objective is reached.

Biofuel
Biofuel from trees, which contains, for example from the Chernobyl accident, is an issue where SSI is currently conducting research and formulating regulations.



Cosmic radiation
Airline flight crews can be exposed to high levels of cosmic radiation. SSI participates in joint international projects to identify the occupational exposure within this job category.

Electromagnetic fields
SSI is working on the risks associated with electromagnetic fields and adopts countermeasures when risks are identified.

Emergency preparedness
SSI maintains a round-the-clock emergency response organisation to protect people and the environment from the consequences of nuclear accidents and other radiation-related accidents.

SSI Education
is charged with providing a wide range of education in the field of radiation protection. Its courses are financed by students' fees.

EDITORS / REDAKTÖRER : Richard Kłos

TITLE / TITEL: The Generalised Ecosystem Modelling Approach in radiological assessment/ Generaliserad ekosystemsmodellering för radiologisk konsekvensanalys

DEPARTMENT / AVDELNING: of Nuclear Facilities and Waste Management / Avdelningen för kärnteknik och avfall

SSI rapport: 2008:09
mars 2008
ISSN 0282-4434

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Foreword

This report presents biosphere modelling in support of the review of the Swedish Nuclear Fuel and Waste Management Co's (SKB) safety report SR-Can carried out by SSI's modelling team, CLIMB. The CLIMB review report (SSI Report 2008:08) is, in turn, a supporting document for the joint review of SR-Can by SSI and the Swedish Nuclear Power Inspectorate (SKI). The authorities review report is published in a joint SSI/SKI report (SSI Report 2008:04 E; SKI Report 2008:23).

SKB plans to submit a license application for the construction of a repository for spent nuclear fuel in Sweden 2010. In support of this application SKB will present a safety report, SR-Site, on the repository's long-term safety and radiological consequences. As a preparation for SR-Site, SKB published the preliminary safety assessment SR-Can in November 2006, documenting a first evaluation of long-term safety for two candidate sites Forsmark and Laxemar.

An important objective of the authorities' review of SR-Can is to provide regulatory guidance to SKB on the complete safety reporting for the license application. The authorities have engaged external experts for independent modelling, analysis and review, with the aim to provide a range of expert opinions related to the sufficiency and appropriateness of various aspects of SR-Can.

This report presents model development and modelling carried out by SSI's consultant, Richard Kłos. A generic modelling approach has been developed and used as a means of evaluating the radiological impact of radionuclide release to the surface environment in SKB's SR-Can assessment. The conclusions and judgements in this report are those of the author and may not necessarily coincide with those of SKI and SSI. The authorities own review will be published separately (SKI Report 2008:23, SSI Report 2008:04 E).

Shulan Xu (leader of the CLIMB modelling team)

Förord

Den här rapporten redovisar biosfärsmodellering som utförts till stöd för SSI:s modelleringsgrupp CLIMB i dess granskning av Svensk Kärnbränslehantering AB:s (SKB) säkerhetsredovisning SR-Can. CLIMB:s granskning (SSI Rapport 2008:08) utgör i sin tur ett underlag för SSI's och Statens kärnkraftinspektions (SKI) gemensamma granskning av SR-Can (SSI Rapport 2008:04; SKI Rapport 2008:19).

Svensk kärnbränslehantering AB (SKB) planerar att lämna in en ansökan om uppförande av ett slutförvar för använt kärnbränsle i Sverige under 2010. Som underlag till ansökan kommer SKB presentera en säkerhetsrapport, SR-Site, som redovisar slutförvarets långsiktiga säkerhet och radiologiska konsekvenser. Som en förberedelse inför SR-Site publicerade SKB den preliminära säkerhetsanalysen SR-Can i november 2006, vilken redovisar en första bedömning av den långsiktiga säkerheten vid SKB:s två kandidatplatser Laxemar och Forsmark. Myndigheternas granskning syftar till att ge SKB vägledning inför den planerade tillståndsansökan. Myndigheterna har i sin granskning tagit hjälp av externa experter för oberoende modellering, analys och granskning.

Modelleringen som redovisas i denna rapport har genomförts av SSI's konsult Richard Kłos. En flexibel compartment-modell har utvecklats och använts som ett verktyg för att utvärdera de radiologiska konsekvenserna från utsläpp av radionuklider till ytmiljön i SKB:s säkerhetsanalys SR-Can. Slutsatserna och bedömningarna i denna rapport är författarens egna och överensstämmer inte nödvändigtvis med SSI:s ställningstaganden.

Shulan Xu (ansvarig för SSI:s modelleringsgrupp CLIMB)

Sammanfattning

SSI behöver en oberoende modelleringskompetens för att kunna utvärdera de doskonsekvensanalyser som görs av SKB. Fokus ligger på utvärdering av den långsiktiga radiologiska säkerheten för slutförvar för både använt kärnbränsle och lågaktivt radioaktivt kärnavfall.

SSI startade modelleringsgruppen CLIMB (Catchment LInked Models of radiological effects in the Biosphere) år 2004 för att utveckla nya modeller som kan användas som oberoende modelleringsverktyg i säkerhetsanalys. Ett av resultaten är utvecklingen av GEMA (*generalised ecosystem modelling approach)* modellen.

GEMA är boxmodeller med ett modulsystem för att beskriva radionukliders omsättning i ytmiljön. Det kan konfigureras, genom vatten- och materialflöden, för att beskriva en rad av ekosystem i det svenska landskapet. Modellen är generell, men finjustering kan göras med hjälp av lokala detaljer om ythydrologi.

The modular nature of the modelling approach means that GEMA modules can be linked to represent large scale surface drainage features over an extended domain in the landscape. System change can also be managed in GEMA, allowing a flexible and comprehensive model of the evolving landscape to be constructed. Environmental concentrations of radionuclides can be calculated and the GEMA dose pathway model provides a means of evaluating the radiological impact of radionuclide release to the surface environment.

Modulegenskaperna innebär att GEMA-moduler kan kopplas ihop och beskriva storskaliga avrinningsområden i landskapet. GEMA tillåter även beskrivning av ett landskap som utvecklas i tiden. Miljökoncentrationer av radioaktiva ämnen kan beräknas och dosmodellen i GEMA gör det möjligt att utvärdera de radiologiska konsekvenserna av utsläpp till ytmiljön.

Det här dokumentet redovisar principerna bakom GEMA-modellen och dess funktionalitet och illustreras med beräkningsexempel som genomförts till stöd för SSI:s granskning av SR-Can.

Summary

An independent modelling capability is required by SSI in order to evaluate dose assessments carried out in Sweden by, amongst others, SKB. The main focus is the evaluation of the long-term radiological safety of radioactive waste repositories for both spent fuel and low-level radioactive waste.

To meet the requirement for an independent modelling tool for use in biosphere dose assessments, SSI through its modelling team *CLIMB* commissioned the development of a new model in 2004, a project to produce an integrated model of radionuclides in the landscape. The *generalised ecosystem modelling approach* (*GEMA*) is the result.

GEMA is a modular system of compartments representing the surface environment. It can be configured, through water and solid material fluxes, to represent local details in the range of ecosystem types found in the past, present and future Swedish landscapes. The approach is generic but fine tuning can be carried out using local details of the surface drainage system.

The modular nature of the modelling approach means that GEMA modules can be linked to represent large scale surface drainage features over an extended domain in the landscape. System change can also be managed in GEMA, allowing a flexible and comprehensive model of the evolving landscape to be constructed. Environmental concentrations of radionuclides can be calculated and the GEMA dose pathway model provides a means of evaluating the radiological impact of radionuclide release to the surface environment.

This document sets out the philosophy and details of GEMA and illustrates the functioning of the model with a range of examples featuring the recent CLIMB review of SKB's SR-Can assessment.

Contents

1 INTRODUCTION

1.1 Background

As the regulatory authority for radiological protection in Sweden SSI has instigated *Projekt CLIMB* – Catchment LInked Models of radiological effects in the Biosphere – as a means of carrying out numerical assessments of the potential impact of radionuclide releases to the surface environment following disposal of spent fuel and other radioactive wastes in deep geologic repositories. The biosphere assessment model developed in CLIMB is GEMA – the generic ecosystems modelling approach.

GEMA provides SSI with the capability to carry out independent numerical evaluations of releases of radionuclides to biosphere systems typical of those associated with SKB's candidate sites for a disposal facility for spent radioactive fuel. The models developed in CLIMB have been employed in a review (Xu *et al*., 2008) of the SR-Can assessment (SKB, 2006a).

An essential feature of GEMA is that radionuclide transport and accumulation in the biosphere is modelled over spatially extended regions. A modular representation of ecosystems within the overall surface drainage system is constructed from the GEMA modules that represent elements of the flowpath network. The modular approach also allows conditions in the system to change in time so that models of the evolving landscape system can be constructed.

This document provides a description of the modelling philosophy, the detail of the individual ecosystem sub-models and the application of the model.

1.2 Outline of the report

A review of SKB's documentation of models for dose assessment prior to SR-Can, particularly SKB (2004), the interim SR-Can documentation, suggested a basic modular structure for GEMA. This structure is discussed in Section 2.1 below. The representation of transfer processes in the physical transfer model is reviewed in Section 2.2 and the exposure pathways models are set out in Section 2.3. Section 2.4 describes how a landscape model is configured using the GEMA module. It also outlines how system change can be represented.

As with many biosphere assessment models, GEMA is somewhat data intensive and this is compounded by the need to represent the extended landscape in both time and space. GEMA is intended specifically for interpretation of radiological assessments of candidate sites for geological disposal facilities proposed by SKB in Sweden. Interpretation of site data in GEMA is a key issue. Section 3 illustrates how elements of the SKB's extensive site descriptive database are used to populate GEMA's datasets. The GEMA models discussed here are based on an independent interpretation of site descriptive data for Forsmark and Laxemar (Lindborg, 2005; 2006). Section 3 also shows how the GEMA datasets are constructed after identifying time invariant and time varying parameters. A full reference dataset for the exposure pathway submodel is also given for reference.

To illustrate the application of GEMA, results are discussed in Section 4 featuring two objects in the Laxemar landscape and a non-evolving model of contaminant transport through a simplified model of the present day Forsmark landscape. Section 5 has some concluding remarks.

2 THE GEMA MODULE

2.1 Ecosystem types – a generic model

At the time of the SR-Can interim assessment in 2004 (SKB, 2004) SKB had clearly identified the different types of ecosystem necessary to model the evolution of the biosphere at the Forsmark and Laxemar sites. For example, the 2500 AD Forsmark site was judged to comprise:

Marine areas (2 locations)
Mire (6)
Lake (3)
Forest (1)
Running water (1).

While this is neither exhaustive nor wholly representative of the site potentially affected by release of radionuclides at 2500 AD, the types of ecosystem are typical according to (SKB, 2006a) and the ecosystem models used are in SR-Can are similar to those described in earlier assessments (Avila, 2006). To this may be added areas of agricultural land. To offer the greatest degree of flexibility the decision was made that the CLIMB biosphere model would use a generic structure of eight compartments to allow combinations of terrestrial and aquatic ecosystems. This structure is shown in Figure 2.1. The terrestrial sub-model comprises upper (rooting zone) soil with a deeper soil layer overlying less weathered Quaternary deposits (QD). A litter layer can be modelled above the soil layers. In the aquatic sub-model sediment is represented as two layers to allow the upper sediment layer to have different characteristics from the deeper material. Furthermore, to allow for modelling of deep bays and lakes there can be two layers of the water column.

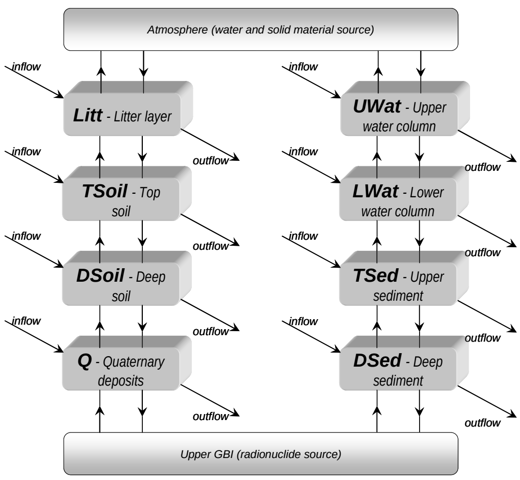


Figure 2.1. The GEMA module. Elements of the flow path are represented by the eight compartments. Material flows from upstream to downstream can be included. Flows to and from the atmosphere and geosphere-biosphere interface are an integral part of the mass balance scheme. The short names of the compartments illustrated are used as suffixes when writing the GEMA equations: Q = Quaternary deposits, LWat = lower water, etc.

The inclusion of compartments for both terrestrial and aquatic structural elements within the same modular framework allows a number of practical modelling features: all model elements have representative hydrology which allows in- as well as outflows. Mass balance (for water fluxes, solid material fluxes and, automatically thereby, radionuclides) is the basis for the model representation in each module. Integration into a landscape model in which the different elements of the drainage system flowpath exchange material is therefore straightforward (see Section 2.4).

Different ecosystems representations may not require that all compartments are involved at all times. For example the *litter layer* is only required for modelling forest (including natural scrubland). Many mainly aquatic modules only need the lower water column (e.g., rivers, shallow lakes and bays). Compartments can be switched in and out as required during the evolution of the system.

Over short timescales evolution can be modelled by the gradual change in properties of the individual compartments. Over longer periods accounting for changes in geometry and structure can require some compartments to be turned on or off. Accounting for the accumulated contamination then requires that some inventories be transferred to other compartments within the same module. Over the longest timescales the overall nature of the ecosystem at any particular spatial location might change such that the characteristics differ completely those at the earlier time. Mass conservation requires that the inventory at the earlier time be transferred appropriately to the compartments at the later time.

Both gradual (successionary) changes can be modelled – e.g., sedimentation within lakes and bay – as well as sudden changes such as the transformation of wetland areas to farmland by human action.

The generic GEMA FEP matrix is shown in Appendix A.

2.2 Transfer processes and environmental concentrations

GEMA uses a traditional compartment modelling approach to represent radionuclides transport and accumulation in the environment. The dynamics of the radionuclide inventories (expressed as Bq) in the eight shown in Figure 2.1 are given by

$$\frac{d\mathbf{N}}{dt} = \mathbf{\Lambda N} + \lambda_N (\mathbf{M} - \mathbf{N}) + \mathbf{S}(t) \text{ Bq y}^{-1}, \tag{2.1}$$

where **N** is the vector of compartment contents (Bq) of radionuclide *N* and **M** is the content of parent nuclide *M*. The decay constant for *N* is λ_N y^{-1} and external sources (inputs) are $\mathbf{S}(t)$. Intercompartment transfers are given by the matrix $\mathbf{\Lambda}$ y^{-1}. The solution to this equation is implemented at SSI using *Matlab*®. Details are given in Appendix B.

The compartment model approach uses transfer coefficients to model the fractional transfer between compartments in the module. The transfer matrix $\mathbf{\Lambda}$ has elements, λ_{ij} y^{-1}, which transfer radionuclides from compartment *i* to compartment *j*. The transfer coefficients are the fractional transfer rates between compartments via a number of concurrent FEPs, *k*. The linearity of the system means that the FEPs can be combined simply:

$$\lambda_{ij} = \frac{1}{N_i} \sum_{\substack{FEPs \\ k}} \frac{dN_{ij}^k}{dt} \text{ y}^{-1}. \tag{2.2}$$

For transfers driven by water (F_{ij} m^3 y^{-1}) and solid material fluxes (M_{ij} kg y^{-1}) this becomes

Quaternary deposit, soils, sediments

$$\lambda_{ij} = \frac{1}{V_i} \cdot \frac{F_{ij} + k_i M_{ij}}{\theta_i + (1-\varepsilon_i)\rho_i k_i} \text{ y}^{-1}, \tag{2.3a}$$

Water bodies:

$$\lambda_{ij} = \frac{F_{ij} + k_i M_{ij}}{V_i} \text{ y}^{-1}. \tag{2.3b}$$

The compartment volume is V_i m^3, with porosity ε_i and volumetric moisture content θ_i. Density of the parent material is ρ_i kg m^{-3} and the solute – solid distribution coefficient is k_i (Bq kg^{-1})(Bq m^{-3})$^{-1}$. Equation (2.3a) allows for local variations in bulk density to be explicitly addressed, based on the structural properties of the compartment.

Modelling in GEMA modules thus depends on the identification the environmental drivers – the water and solid fluxes. Each GEMA module has a water flux matrix, **F** m^3 y^{-1}, and a solid material flux matrix , **M** kg y^{-1}, defined. These matrices express flux conservation spatially – inflow and outflow balance is evaluated – and temporally as the compartments change in time.

Concentration in environmental media can be calculated in a variety of ways. The most straightforward is to take the compartmental inventories, obtained from the solution to Equation (1.1), to determine the volumetric concentration:

$$C_i = \frac{N_i}{V_i} \text{ Bq m}^{-3}. \tag{2.4}$$

Other forms are possible but these can be evaluated from this basic definition using the compartment characteristics. For example, the unfiltered porewater concentration in compartment *i* representing an aquifer is given by

$$C_i^p = \frac{1+\alpha_i k_i}{\theta_i + (1-\varepsilon_i)\rho_i k_i} \frac{N_i}{V_i} = \frac{1+\alpha_i k_i}{\theta_i + (1-\varepsilon_i)\rho_i k_i} C_i \text{ Bq m}^{-3}, \tag{2.5}$$

which takes into account not only the dissolved radionuclide but also the amount sorbed into suspended solid material present in the porewater as suspended solid load α_i kg m^{-3}.

The concentration per wet weight or dry weight soil can be found by similar manipulation of Equation (2.4).

2.3 Exposure pathways

2.3.1 Basis

Evaluation of annual individual dose requires an estimation of the degree of interaction between contaminated media and hypothetical individuals comprising the "critical group" on an annual basis[1]. Exposure is via ingestion, inhalation or external irradiation and each of these are related back to the concentrations given by Eq. (2.4). Ingestion includes all pathways entering through the gastrointestinal tract including foodstuffs and water as well as any direct consumption of soil particles. Inhalation doses are via radionuclides breathed into the lungs. External irradiation accounts for contaminated environmental media exposing the body of exposed individuals.

2.3.2 Ingestion dose

Ingestion doses are calculated using the dose conversion factor for ingestion, H_{ing} Sv Bq^{-1}, to evaluate the annual dose on the basis of annual intake:

$$D_k = H_{ing} I_k C_k \text{ Sv y}^{-1}, \tag{2.6}$$

as I_k (kg y^{-1}) is the annual intake of medium *k* with concentration C_k (Bq kg^{-1} or Bq m^{-3}).

Intake rates are largely determined by diet of different foodstuffs available from the ecosystem module but foodstuff concentrations are related to the media concentrations. Both soil and water concentrations might be involved in the production of a particular foodstuff. For example, accumulation in cultivated crops might involve the top soil together with well, lake or river water if the crop is irrigated. Animals might consume locally produced foodstuffs as well as water. Local conditions in the ecosystem determine which media are involved.

In general the expression for the concentration in foodstuff *k* is given by:

---

1 The "critical group" concept is used here to indicate a group of individuals for whom radiological exposures are the highest within the societal context of the modelled system. The usage is synonymous with the "most exposed group" and assumes a pattern of behaviour which maximises exposure to foodstuffs and other environmental media in a realistic manner. That all of the exposure pathways are assumed be active at these rates of exposure makes them conservative. The SKB concept used in SR-Can (SKB, 2006a) differs somewhat.

$$C_k = \sum_i P_{ki} C_i \text{ Bq kg}^{-1} \text{ or Bq m}^{-3}. \tag{2.7}$$

The elements P_{ki} are the *processing factors* which convert the environmental distribution of radionuclides into concentrations in ingested material. The way they are calculated in GEMA is shown in Table 2.1. The foodstuff types associated with the different ecosystems are shown in Table 2.2.

2.3.3 Inhalation doses

Inhalation comes only from suspended dust derived from the top soil or a combination of the top soil and litter layers in the forests:

$$D_{inh} = H_{inh} O_e I_b \alpha_{air} \frac{\sum_{i=TSoil,Litt} l_i C_i^{dry}}{\sum_{i=TSoil,Litt} l_i} \text{ Sv y}^{-1}. \tag{2.8}$$

H_{inh} Sv Bq^{-1} is the dose per unit intake on inhalation and O_e hours y^{-1} the occupancy of ecosystem *e*. The breathing rate is I_b m^3 hour^{-1} and the dust concentration in air is α_{air} kg m^{-3}. The average concentration in air is based on the dry concentration in both TSoil and Litt,

$$C_i^{dry} = \frac{1}{(1-\varepsilon_i)\rho_i + \varepsilon_i \rho_{LWat}} \frac{N_i}{V_i}, \; i = TSoil, Litt \text{ Bq kg}^{-1} \text{ (dw)}. \tag{2.9}$$

2.3.4 External irradiation

Like inhalation, external irradiation uses an occupancy factor:

$$D_{ext} = H_{ext} O_e \frac{\sum_{i=TSoil,Litt} l_i C_i^{wet}}{\sum_{i=TSoil,Litt} l_i} \text{ Sv y}^{-1}. \tag{2.10}$$

which uses the wet soil concentration:

$$C_i^{wet} = \frac{1}{(1-\varepsilon_i)\rho_i} \frac{N_i}{V_i}, \quad i = TSoil, Litt \text{ Bq kg}^{-1} \text{ (ww)}. \tag{2.11}$$

Table 2.1. GEMA processing factors for ingestion pathways.

Type	Pathway	Expression	Comments
Water consumption	Surface water	$C_{dw} = \frac{N_i}{V_i}$	Lakes or rivers, *i* = *LWat* or *Uwat* depending on the water body concerned.
	Well water	$C_{well} = \frac{1+\alpha_i k_i}{\theta_i + (1-\varepsilon_i)\rho_i k_i} \frac{N_i}{V_i}$	Aquifer: usually in the Quaternary deposits, compartment *Q*.
Plant produce	Root uptake	$C_{crop}^{root} = K_{crop} \frac{1}{(1-\varepsilon_i)\rho_i} \frac{N_i}{V_i}$	Crops contaminated by root uptake, grown on TSoil or Litt (fungi in forest areas). Uptake factor for wet soil
	Irrigation interception	$C_{crop}^{irri} = \left(f_{crop} + \frac{T_{crop}}{H_{crop}} \right) \frac{f_{intercep} d_{irri}}{Y_{crop}(W_{crop} + H_{crop} + T_{crop})}$	Irrigation deposition intercepted by plant and incorporated in edible tissues.
		$d_{irri} = \frac{1+\alpha_a k_a}{\theta_a + (1-\varepsilon_a)\rho_a k_a} \frac{N_a}{V_a} \frac{F_{aTSoil}}{A_i} + \frac{N_s}{V_s} \frac{F_{sTSoil}}{A_i}$	Concentration and amount of irrigation derived from aquifer or surface water
	Soil	$C_{soil} = \frac{1}{(1-\varepsilon_i)\rho_i + \varepsilon_i \rho_{LWat}} \frac{N_i}{V_i}$	Inadvertent consumption of dry soil
Animal produce	Meat	$C_{meat} = K_{meat} \left[\sum_p I_p C_p + \sum_w I_w C_w + I_s C_s \right]$	Combination of contaminated plant material, water (stream or well) and soil intake and distribution coefficient for meat
	Milk	$C_{milk} = K_{milk} \left[\sum_p I_p C_p + \sum_w I_w C_w + I_s C_s \right]$	Combination of contaminated plant material, water (stream or well) and soil intake and distribution coefficient for milk

Table 2.2. Plant and animal products consumed by ecosystem type. Food types are those identified by SKB (2001; 2004) and for which Karlsson et al. (2001) give uptake and concentration factors.

Ecosystem	Food type, *k*
Sea	Fish
Lake	Fish, freshwater invertebrates
Stream	Fish, freshwater invertebrates
Forest	Game, fruit, nuts, berries, fungi
Agricultural land	Meat, milk, cereals, root veg,, leafy veg.

2.4 Landscape modelling and system change

As illustrated in Figure 2.1 each of the eight compartments of the GEMA module can receive external inputs, i.e., inputs either from the geosphere-biosphere interface representing the release function to the biosphere or from material inflows from "upstream" in the biosphere system. For each GEMA module, therefore, the source term $\mathbf{S}(t)$ in Equation (2.1) is potentially made up of two components:

- Release from the geosphere
- Inflow from upstream GEMA modules.

A third type of "source term" is ingrowth from the precursor nuclide but this is expressly handled in Equation (2.1).

A GEMA landscape model is therefore constructed from a network of modules passing radionuclides between them. Landscape models take into account the change in properties. For example, in modelling a deep lake with both LWat and Uwat compartments draining via a stream the modeller is expected to distinguish between outflows from lower and/or upper water. The role of groundwater fluxes in the Quaternary material is also relevant. In practice individual models of different parts of the drainage system must take into account local hydrologic conditions. Transfers from one GEMA module to another use a matrix to transform the output from the upstream module to match conditions downstream. In many cases the identity matrix can be used but the option is included to represent more detailed interfaces should the need arise.

A similar situation arises in the case of system evolution. When change is modelled as a step event a matrix representation is used partition the accumulated activity between compartments in the module. This is the case in the application discussed in Section 3.2 of this report. In principle gradual change can be modelled as sequence of steps with each system state being modelled over a short interval. However, it is convenient model gradual change using modified internal transfer factors. In this way the transfer factors between model timesteps take into account the change in compartment volumes within the GEMA module. An example is the gradual fall of water level in lakes with the formation of soil. As water level falls there is a transfer of sediment to terrestrial soil which is modelled as a change of compartment volume. This corresponds to a water flux from DSed to Q given by

$$F^{evolution}_{\substack{DSed\\Q}} = \theta_{DSed} L_Q \frac{dA_{TSoil}}{dt} \text{ m}^3 \text{ y}^{-1}, \quad (2.12)$$

where the FEP is "evolution", in the notation of Equation (2.2). There is also a corresponding flux of solid material. These two processes combine to define the system change-driven transfer coefficient using Equation (2.3a). The two forms – matrix and modified transfer coefficient – can be readily shown to be equivalent.

Details of these processes may vary for each application. Section 3.2.4 illustrates one such application and the results discussed in Section 4.1 further investigate the implications for assessment models.

2.5 GEMA implementation

Implementation of GEMA employs Excel files to store data and results for each module. These are illustrated in Appendix C. The GEMA codes used to calculated the time series of inventories, concentrations and doses are written in Matlab and the controlling code to integrate the model are also outlined in Appendix C.

3 GEMA DATASETS

3.1 Background

This section discusses the generation, for GEMA applications, of datasets from site descriptive data and models. The structural model outlined in the preceding section relies on site data for specificity. Obviously, the application can include as much detail as is supported the site characterisation database. The SKB site descriptive models for Forsmark and Laxemar (Lindborg, 2005; 2006) provide a comprehensive resource on which GEMA interpretations can be based. The three numerical examples given here use different levels of detail:

1. the evolution of a large bay at Laxemar (Basin Borholmsfjärden);
2. the evolution of a small, shallow lake which has recently formed in an isolated catchment at Laxemar, just to the north of Borholmsfjärden; and
3. an example of radionuclide transport through a simplified representation of landscape elements around lake Bolundsfjärden at Forsmark.

The Lindborg (2005; 2006) site descriptions contain several essential modelling details, including topographic maps, the thickness of the Quaternary deposits, locations surface water bodies (bays, lakes, wetlands and streams) as well as soil types and vegetation classification.

The focus here is on the procedure used to derive the intercompartmental transfer factors – the elements of the matrix $\mathbf{\Lambda}$ in Equation (2.1) via the expressions in Equations (2.3). $\mathbf{\Lambda}$ determines the distribution of contaminants in the surface system and its elements depend explicitly on the water and solid material fluxes internally within the ecosystem module as well as externally in the larger scale landscape model. In describing $\mathbf{\Lambda}$ extensive use is made of the topographic maps combined with details of local hydrology (primarily precipitation and evapotranspiration estimates).

Basin Borholmsfjärden is illustrated here because it was the main feature of the Xu et al. (2008) review of SR-Can. The steps taken to derive the GEMA representation of the northern part of the bay are discussed in Section 3.2, together with the model for a small isolated catchment to the north of Borholmsfjärden. This section of the report provides a guide to the procedure for interpreting site descriptive model. These models illustrate one approach to system evolution using GEMA.

A simplified model of elements of the lake Bolundsfjärden drainage system is presented in Section 3.3. This model illustrates radionuclide migration along a spatially extended surface drainage network.

Radionuclide specific data used in the GEMA models are given in Section 3.4. K_d values are linked to site conditions but uptake and accumulation factors are more generic. Existing SKB datasets are used for these purposes. The numerical data used in GEMA are also listed in Section 3.4.

Models of exposed group behaviour are similarly based on existing SKB publications (Section 3.5). The Exposure Group model employed in GEMA differs somewhat from that used in SR-Can (SKB, 2006a) so the numerical values are listed in full. Local societal conditions determine which exposure pathways are active in any particular GEMA module. The interpretation used in the Laxemar models is also discussed in 3.5.

Table 3.1. GEMA discretisation of the Laxemar landscape objects shown in Figure 3.1. The GEMA flowpath elements identifiers for the different object interpretations are noted, these are used throughout this report.

Landscape object	sub-catchment(s)	GEMA FPE ID
Borholmsfjärden	Northern Borholmsfjärden	LF2:01
Borholmsfjärden	Central Borholmsfjärden	LF2:02
	Western Borholmsfjärden	
S Getbergsfjärden	S Getbergsfjärden	LF2:03
(as modelled in SR-Can)		
Borholmsfjärden	Northern Borholmsfjärden	LF2:02a
(as modelled in SR-Can)	Central Borholmsfjärden	
	Western Borholmsfjärden	
Borholmsfjärden	Western Borholmsfjärden	LF2:02d
Borholmsfjärden	Central Borholmsfjärden	LF2:02c
Borholmsfjärden *extreme*	Borholmsfjärden *extreme*	BRH_x

3.2 An evolving system: Basin Borholmsfjärden, Laxemar

3.2.1 Landscape features

The GEMA models here describe the surface drainage system comprising two basins at the Laxemar candidate site: Borholmsfjärden and S Getbergsfjärden. Figure 3.1 is a map of the area based on the SKB topographic dataset for the Laxemar site SDEADM.UMEU_SM_HOJ_2102 (Lindborg, 2006) provided by SKB. The release points calculated by SKB in SR-Can are also plotted to illustrate the parts of the surface drainage system that might receive input. Today the basins connect to the Baltic.

In SR-Can (SKB, 2006a) Borholmsfjärden was modelled as a single object with S Getbergsfjärden as a second object downstream. As indicated in Figure 3.1 the GEMA interpretation recognises that basin Borholmsfjärden can be described by three sub-catchments. The Laxemar catchments (SKB datafile SDEADM.POS_SM_VTN_3286) is used for this purpose. However, catchments around coastal objects are not explicitly identified so the sub-catchments of Borholmsfjärden have been determined by a review of the topography. The interpretation of the objects is shown in Table 3.1.

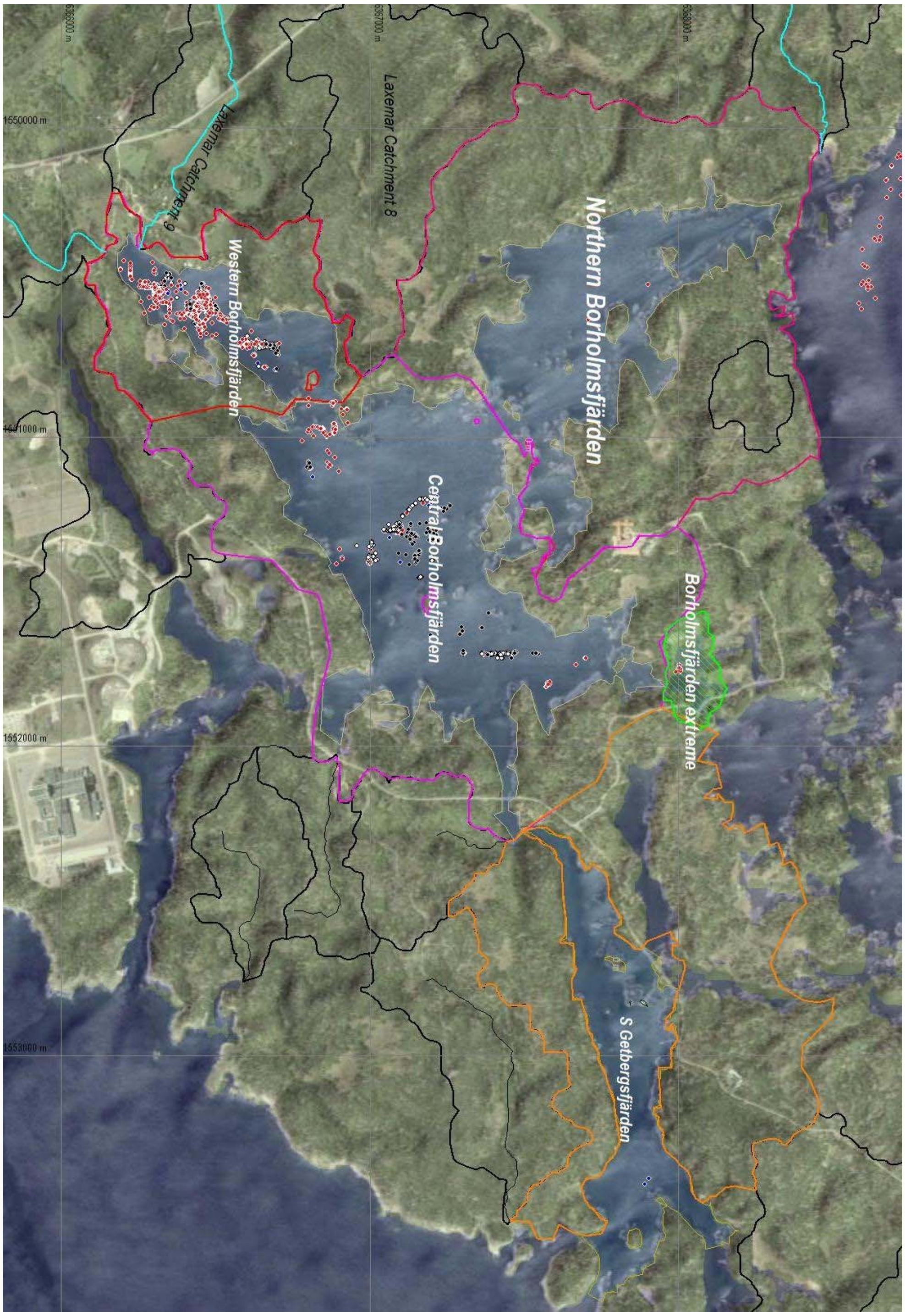


Figure 3.1. Map of Laxemar in the present day showing drainage system from Laxemar catchments 8, 9 and 10. Coloured areas show the local catchments of the basins. In the GEMA discretisation of Basin Borholmsfjärden one, two or three distinct objects can be identified where SR-Can (SKB, 2006a) identifies just one. Northern Borholmsfjärden is the main focus since it has no inflow from upstream catchments. To the northeast of Borholmsfjärden is a smaller isolated catchment identified as Borholmsfjärden extreme. Release points are taken from SKB (2006a). Topographic map from SKB (Lindborg 2006)

with overlay image taken from GoogleEarth ™ and fitted to the map using Global Mapper (2007).

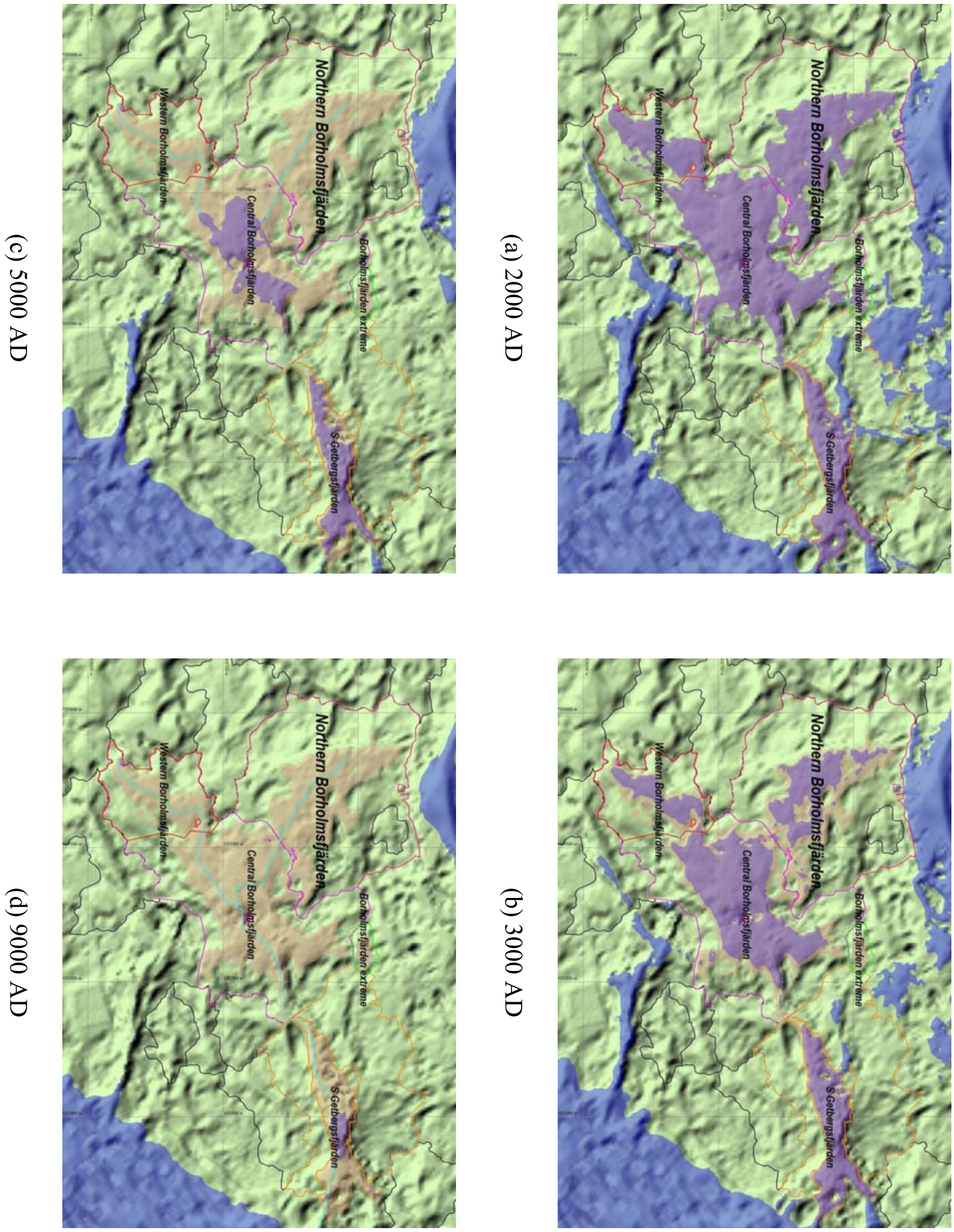


Figure 3.2. Four stages in the evolution of Laxemar's bays. Land rise at 1 mm y^{-1} means 1 m of elevation in 1000 years. Within the present day catchment areas the water bodies retreat and new soil emerges. By 5000 AD the whole of northern Borholmsfjärden is above sea level. Converted to an agricultural area, drainage will be by a stream network.

By 9000 AD all of Borholmsfjärden is a terrestrial system. Water bodies are shown in purple with the emergent land indicated by orange shading.

The interpretation of objects is important for the description of mass balance. Basin Borholmsfjärden is part of the larger Laxemar drainage system. Lindborg (2006) notes that Laxemar catchments 8, 9 and 10 discharge into Borholmsfjärden. By subdividing the basin dilution is much less for some GEMA objects than for the whole of the bay. For example, the northern bay does not receive any drainage inflow. The potential for dilution in the water body is therefore much reduced compared to the overall objects. The northern basin (LF2:01) is the reference for the GEMA modelling. For this reason, the object identified as Borholmsfjärden *extreme* has also been modelled using GEMA, since it could receives a contaminant discharge. Section 3.2.5 describes this area in greater detail.

3.2.2 Landscape evolution at Laxemar

Lindborg (2006) provides basic data for the site description. Of central importance is the local land uplift rate of 1 mm y^{-1}. SR-Can evaluated releases upto 10 000 AD. In the GEMA interpretation evolution was implemented as a series of step changes occurring at each one thousand years starting from the landscape at 2000 AD. The emergent land is illustrated in Figure 3.2.

Land rise is an ongoing processes and succession provides a guide for interpreting the ecosystem types during site evolution. The terrestrial landscape in the present day indicates the kinds of ecosystems that will form as the Baltic retreats. Table 3.2 lists the interpretation of the objects. The general trend is that marine bays become isolated losing their salt content, to form freshwater lakes. Continued sedimentation and plant growth, combined with progressive falls in local sea level produce wetland areas.

During the evolution of bays to lakes and wetlands the emergent soils are rapidly colonised by terrestrial species. These soils are not managed and are designated here as “natural soils”. Agricultural soils are assumed to be formed (by human action) as soon as local hydrological conditions allow, i.e., when the wetland area is above sea level. In the GEMA models here agricultural land areas are associated with streams which provide local drainage.

The description of land use types given by Lindborg (2006) gives more detail than the existing radionuclide database can accommodate. For this reason the interpretation of aquatic systems is limited to marine bay (brackish water), lake (freshwater), wetland (freshwater) and stream (see Section 3.4). The terrestrial systems are natural soils (coastal and terrestrial) and agricultural soils. Forests are also part of the system but these are known to be at the higher elevations. According to the release distribution shown in Figure 3.1, none of the existing forested areas are likely to become contaminated.

Figure 3.2 illustrates key features of the evolutionary sequence. In the 1000 years to 3000 AD northern Borholmsfjärden becomes a lake, isolated from the main body of the original bay. The western portion is still connected to the central water body but by 5000 AD both northern and western Borholmsfjärden are above sea level and are interpreted as agricultural land, having passed though a wetland phase. Upto 9000 AD the water body in the central portion of Borholmsfjärden shrinks to a wetland until, it is assumed, it is drained for agricultural use.

Table 3.2. The sequence of ecosystems for the different system discretisations used in the GEMA interpretation of the Laxemar bays.

	Flowpath elements - GEMA objects						
date	LF2:01	LF2:02	LF2:03	LF2:02a	LF2:02d	LF2:02c	BRH_x
2000 AD	BCS	BCS	BCS	BCS	BCS	BCS	LNS
3000 AD	LNS	LNS	LNS	LNS	LNS	LNS	WNS
4000 AD	WNS	LNS	LNS	LNS	WNS	LNS	SAS
5000 AD	SAS	WNS	LNS	WNS	SAS	WNS	SAS
6000 AD	SAS	WNS	LNS	WNS	SAS	WNS	SAS
7000 AD	SAS	WAS	LNS	WAS	SAS	WAS	SAS
8000 AD	SAS	WAS	LNS	WAS	SAS	WAS	SAS
9000 AD	SAS	SAS	WNS	SAS	SAS	SAS	SAS
10000 AD	SAS	SAS	WNS	SAS	SAS	SAS	SAS

key	Aquatic	Terrestrial
BCS	Bay	Coastal / Natural soils
LNS	Lake	Natural soils
WNS	Wetland	Natural soils
WAS	Wetland	Agricultural soils
SAS	Streams	Agricultural soils

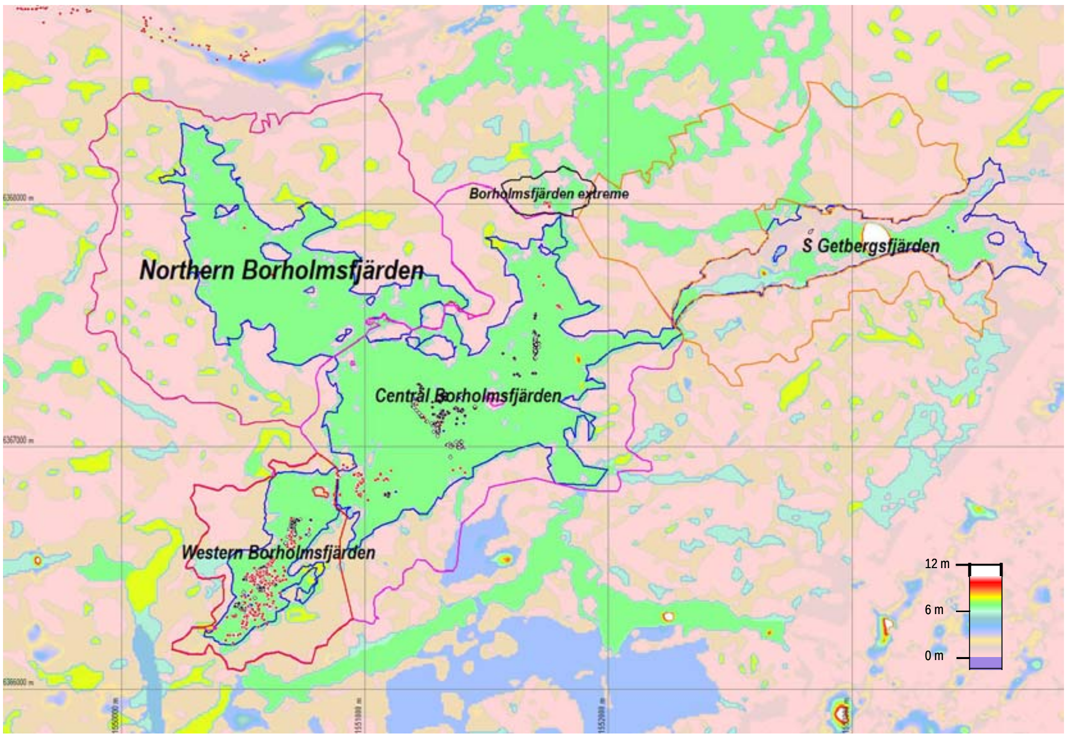


Figure 3.3. Thickness of the QD in the model region. Sediment thickness in the bays is fairly constant at around 7.4 m in Borholmsfjärden. A high fraction of S Getbergsfjärden has similar thicknesses of sediment. The SR-Can release points indicate that the deep sediment of the water bodies lies above the discharge points.

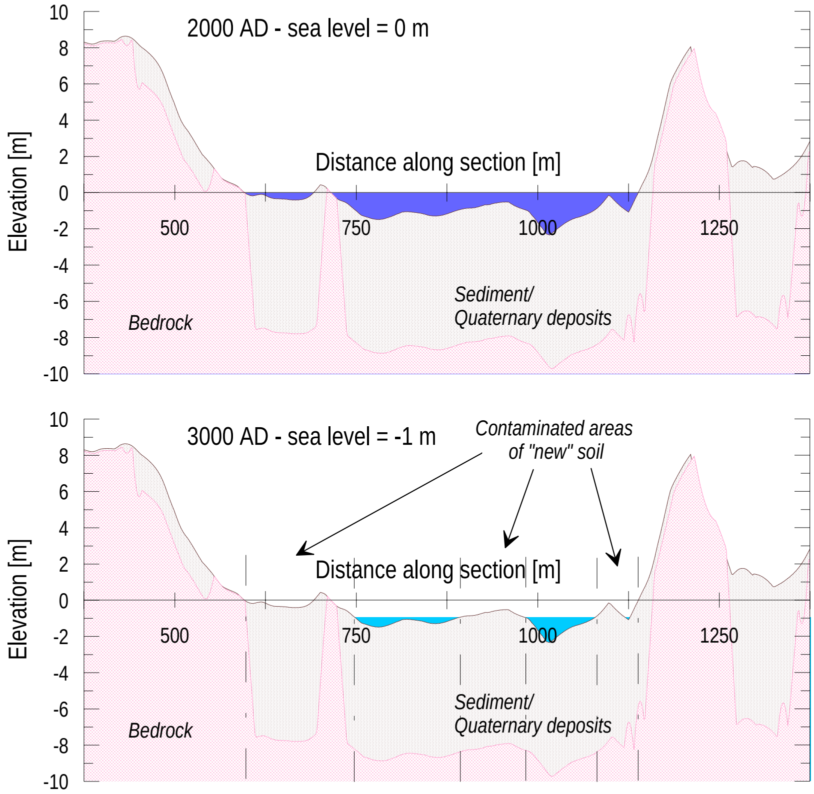


Figure 3.4. Cross section SW-NE across northern Borholmsfjärden (LF2:01) at 2000 and 3000 AD. The bedrock and thickness of Quaternary material are indicated illustrating that the present day terrestrial area would remain as uncontaminated catchment. Topography of bay shoreline for other objects is similar. Emergent soils are indicated.

The spatial discretisation directly effects how the objects are characterised. The reference area, LF2:01 (northern Borholmsfjärden), is assumed to be drained and converted to agricultural land at 5000 AD by which time the whole of the object is above sea level. Streams are then managed to provide the necessary drainage. In the case of the whole Borholmsfjärden object (LF2:02a, as interpreted by SKB as a single object) the area is not wholly above sea level until 9000 AD. Nevertheless large areas of relatively flat soils will already have emerged by 5000 AD. These may be interpreted as being available for agricultural production. The water body is shallow and is interpreted as wetland. For this system the ecosystem type is assumed to be Wetland with Agricultural soils. Agricultural soils are the most productive areas and more of the GEMA exposure pathways are active in such areas.

Lindborg (2006) notes that releases from bedrock are generally associated with low points in the topography. This is confirmed by the releases point shown in Figure 3.1. Lindborg (2006) also describes the thickness of the Quaternary deposits (datafile SDEADM.POS_SM_GEO_2653). The thickness map is shown in Figure 3.3.

The release points correspond to the paths taken by release from the individual canisters at the repository depth. In SR-Can, SKB assign an ensemble of releases to a particular ecosystem to the object in question, neglecting the spatial distribution of points within the object. Similarly in GEMA, releases enter the biosphere objects at the lowest points.

In the Borholmsfjärden and Getbergsfjärden objects the releases are therefore to the bottom of the QD. During bay, lake and wetland phases this is interpreted as a release to deep sediment of the aquatic submodel. During agricultural phases it is assumed that the object is well drained and the QD differs from the deep sediment. The top sediment and deep sediment are therefore treated as smaller compartments in the stream's hyporheic zone. Thus, release is to deep sediment unless the object is agricultural land in which case the release is to the QD. This interpretation is reflected in the assumed mass balance schemes for objects in the GEMA representations described in the following section.

3.2.3 Parameterisation of water and solid material balance: transfer coefficients

Equations (2.3) suggest contaminant transport in GEMA is modelled straightforwardly. The volumes of compartments and the internal characteristics are required and mass fluxes determine the contaminant flows. This section illustrates the procedure for determining the fluxes in Equation (2.2).

Lindborg (2006) shows that the Borholmsfjärden – Getbergsfjärden drainage system is part of the flow system of three catchments, identified as Laxemar 8, 9 and 10. These enter the western part of Borholmsfjärden (see Figure 3.1). Laxemar 7 discharges to the north of Borholmsfjärden. Laxemar 8 is small (485481 m^2) but Laxemar 9 and 10 are major catchments at Laxemar, (2755420 m^2 and 47628017 m^2 respectively). Lindborg (2006) gives a range for precipitation and ETp in the Laxemar region. GEMA uses 0.6 m y^{-1} rainfall and 0.5 m y^{-1} for ETp. These values, taken from Bergström and Barkefors (2004), lie within this range[2]. The discharge from the catchments entering the modelled system is then determined as

$$\begin{aligned} F_{inflow} &= \left(d_{ppt} - d_{ETp}\right) A_{catch} \qquad && \mathrm{m^3\,y^{-1}} \\ M_{inflow} &= \alpha_{LWat} F_{inflow} && \mathrm{kg\,y^{-1}} \end{aligned}, \qquad (3.1)$$

where solid material entering the system is assumed to be driven by the suspended solid load in the bay/lake/stream. These flows enter objects connected to the upstream drainage system: LF2:02a for the whole of Borholmsfjärden, LF2:02 when northern Borholms-

---

[2] Precipitation at Laxemar is slightly higher (0.655 m y^{-1}) in SR-Can (SKB, 2006b) and combined evaporation and transpiration, in the forest model slightly lower (0.466 m y^{-1}). These are based on single observations and as such are not necessarily representative of the long term average. At the time that the GEMA models were constructed the details of SR-Can had not been published. The earlier precipitation and ETp values were therefore used in the GEMA calculations. The effect of using the Sr-Can values is to decrease dose by around a factor of up to two for the poorly sorbing nuclides (^{36}Cl, ^{129}I) but much less for the members of the ^{226}Ra chain.

fjärden is treated independently or LF2:02d when three elements of Borholmsfjärden are assumed, see Table 3.1.

At the local level of each GEMA FPE the matrices for water and solid material fluxes are written explicitly. These take into account the interpretation of local hydrology. Figure 3.4 illustrates the typical situation in the modelled area. A SW-NE cut across northern Borholmsfjärden (LF2:01) shows the bedrock, QD and water column of the bay/lake at 2000 AD and 3000 AD. Activity enters the system from the bedrock below the QD. It is assumed that there is a small gradient driving water fluxes up through the sediment. SKB's SR-Can interpretation is different but the assumption made here is that water flows though the QD, allowing time for contaminant retention which is then distributed throughout the sediment for inclusion in emergent soils as they form with the retreat of the water body. Starting from the situation at 2000 AD, contaminated parts of the system are restricted to the areas of sediment underlying the water body. The higher elevations are part of the local catchment but remain uncontaminated. Terrestrial soils only become contaminated as a result of the legacy contamination as the local water level falls.

The higher parts of the system at 2000 AD all have thin QD layers and retain little water. Run off from these areas is assumed to be directly to the water body. As the waters retreat, however, contaminated soils are formed from the sediments under the bay. Water balance is then assumed as shown in Figure 3.5 for the 3000 AD system. Drainage from the uncontaminated higher areas flows to the newly emerged soils where it is assumed to infiltrate and migrate to the water body. This assumption adds to the turnover (and mixing) in the QD and aquatic sediment layers of the model. The assumption reflects the relative lack of understanding of local hydrology.

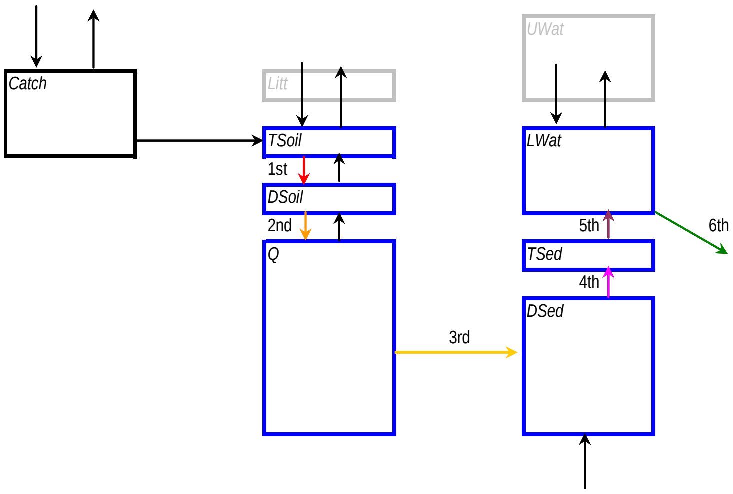
There is a small water flux assumed at the bottom of the system, driven by the water flux from the bedrock with velocity vGBI (taken from SKB, 2006c). Otherwise precipitation and evapotranspiration account for the fluxes. Capillary rise is used to drive the flow from the QD to the top soil. The value is 0.1 m y^{-1} taken from Kłos et al. (1996).

The corresponding solid material scheme is shown in Figure 3.6. For northern Borholmsfjärden the only solid input is from deposition. No details were available for this process so a small value of mdep = 0.01 kg m^{-2} y^{-1} is assumed and this balances erosion with the same value.

As a conservative feature it is assumed that there is no solid flux downstream, cf. the input flux described by Equation (3.1). This manifests itself as net sedimentation in the system, denoted by the flux M_DSed_GBI in Figure 3.6. This flux is used to balance the system since the compartments are maintained constant throughout each 1000 year period. Although there is a mass flux here it is not assumed that radionuclides are included in this transfer. The whole of the accumulated inventory is then available for transfer to land during the next evolutionary step.

Some of the solid fluxes assume suspended solid fluxes with the water flow, using the suspended solid load in the compartments i, α_i kg m^{-3}. This value is taken from Kłos et al. (1996). The other major flux is bioturbation as modelled by Kłos et al. (1996).

The transfer matrix for ^{210}Po in the northern Borholmsfjärden lake at 3000 AD is shown in Figure 3.7. The values are calculated using Equations (2.3) together with the water and solid material fluxes in Figures 3.5 and 3.6.

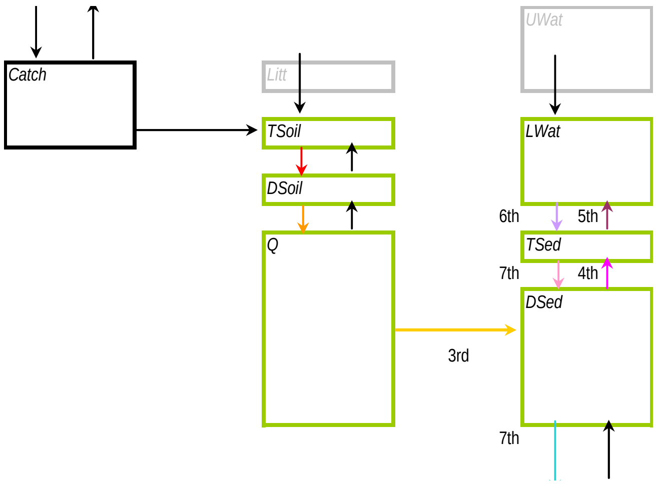


from\to	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow
ATM		6.14E+05			1.79E+05					8.70E+04			
Catch										1.02E+05		5.12E+05	
Dsed				1.34E+05									
Tsed					1.34E+05								
Lwat												1.49E+05	1.642E+05
Uwat													
GBI			1.76E+04										
Q			1.17E+05						1.45E+04				
Dsoil								1.31E+05		1.45E+04			
Tsoil									1.31E+05			7.25E+04	
Litt													
ATMOut													
EcoOutflow													

balance	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow	Total System
in	0.00E+00	6.14E+05	1.34E+05	1.34E+05	3.13E+05	0.00E+00	0.00E+00	1.31E+05	1.46E+05	2.04E+05	0.00E+00	7.33E+05	1.64E+05	
out	8.80E+05	6.14E+05	1.34E+05	1.34E+05	3.13E+05	0.00E+00	1.76E+04	1.31E+05	1.46E+05	2.04E+05	0.00E+00	0.00E+00	0.00E+00	
difference	8.80E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.76E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-7.33E+05	-1.64E+05	0.00E+00

F_inflow_i	=	0		For all i
F_ATM_Catch	=	6.14E+05	=	dppt*ACatch
F_ATM_Lwat	=	1.79E+05	=	dppt*ALWat
F_ATM_Tsoil	=	8.70E+04	=	dppt*ATsoil
F_Catch_Tsoil	=	1.02E+05	=	F_ATM_Catch-F_Catch_ATMOut
F_Catch_ATMOut	=	5.12E+05	=	dETp*ACatch
F_Dsed_Tsed	=	1.34E+05	=	F_GBI_Dsed+F_Q_Dsed
F_Tsed_Lwat	=	1.34E+05	=	F_Dsed_Tsed
F_Lwat_ATMOut	=	1.49E+05	=	dETp*ALWat
F_Lwat_EcoOutflow	=	1.64E+05	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_GBI_Dsed	=	1.76E+04	=	ADSed*vGBI*SIN(phiGBI)
F_Q_Dsed	=	1.17E+05	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q
F_Q_Dsoil	=	1.45E+04	=	dcapil*AQ
F_Dsoil_Q	=	1.31E+05	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	1.45E+04	=	dcapil*ADSoil
F_Tsoil_Dsoil	=	1.31E+05	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut
F_Tsoil_ATMOut	=	7.25E+04	=	dETTSoil*ATsoil

Figure 3.5. Water balance for northern Borholmsfjärden at 3000 AD. A glossary of GEMA parameters is given in Appendix D.



from\to	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow
ATM					2.98E+03					1.45E+03			
Catch					0.00E+00					1.02E+02			
Dsed				1.59E+03			4.56E+03						
Tsed			4.56E+03		1.59E+03								
Lwat				4.56E+03									
Uwat													
GBI			3.51E+01					0.00E+00					
Q			1.55E+03						1.45E+01				
Dsoil								1.57E+03		2.90E+05			
Tsoil									2.91E+05				
Litt													
ATMOut													
EcoOutflow													

balance	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow	Total system
in	0.00E+00	0.00E+00	6.15E+03	6.15E+03	4.56E+03	0.00E+00	4.56E+03	1.57E+03	2.91E+05	2.91E+05	0.00E+00	0.00E+00	0.00E+00	
out	4.43E+03	1.02E+02	6.15E+03	6.15E+03	4.56E+03	0.00E+00	3.51E+01	1.57E+03	2.91E+05	2.91E+05	0.00E+00	0.00E+00	0.00E+00	
difference	4.43E+03	1.02E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.53E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-11

M_inflow _j	=	0		For all i
M_ATM_Lwat	=	2.98E+03	=	mdep*ALWat
M_ATM_Tsoil	=	1.45E+03	=	mdep * ATsoil
M_Catch_Tsoil	=	1.02E+02	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil
M_Dsed_Tsed	=	1.59E+03	=	M_Q_Dsed+M_GBI_Dsed
M_Dsed_GBI	=	4.56E+03	=	M_Tsed_Dsed+M_GBI_Dsed+M_Q_Dsed-M_Dsed_Tsed
M_Tsed_Dsed	=	4.56E+03	=	M_Dsed_Tsed+M_Lwat_Tsed-M_Tsed_Lwat
M_Tsed_Lwat	=	1.59E+03	=	M_Dsed_Tsed
M_Lwat_Tsed	=	4.56E+03	=	M_ATM_Lwat+M_Tsed_Lwat
M_GBI_Dsed	=	3.51E+01	=	alphaDSed*F_GBI_Dsed
M_Q_Dsed	=	1.55E+03	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q
M_Q_Dsoil	=	1.45E+01	=	alphaQ*F_Q_Dsoil
M_Dsoil_Q	=	1.57E+03	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	2.90E+05	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_Tsoil_Dsoil	=	2.91E+05	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil

Figure 3.6. Solid material flux balance for northern Borholmsfjärden at 3000 AD. A glossary of GEMA parameters is given in Appendix D.

transfer matrix	Dsed	Tsed	Lwat	Uwat	Q	Dsoil	Tsoil	Litt	loss
Dsed	-1.83E+00	5.46E-06	0	0	0	0	0	0	0
Tsed	1.45E-04	-1.83E+00	6.98E-04	0	0	0	0	0	0
Lwat	0	2.94E-01	-3.23E+00	0	0	0	0	0	1.11E+00
Uwat	0	0	0	-1.83E+00	0	0	0	0	0
Q	1.01E-05	0	0	0	-1.83E+00	1.08E-06	0	0	0
Dsoil	0	0	0	0	5.04E-04	-1.84E+00	7.24E-03	0	0
Tsoil	0	0	0	0	0	2.06E-02	-1.85E+00	0	0
Litt	0	0	0	0	0	0	0	-1.83E+00	0
loss	0	0	0	0	0	0	0	0	-1.83E+00

Figure 3.7. GEMA transfer coefficients for ^{210}Po in the representation of northern Borholmsfjärden at 3000 AD. The values are calculated from

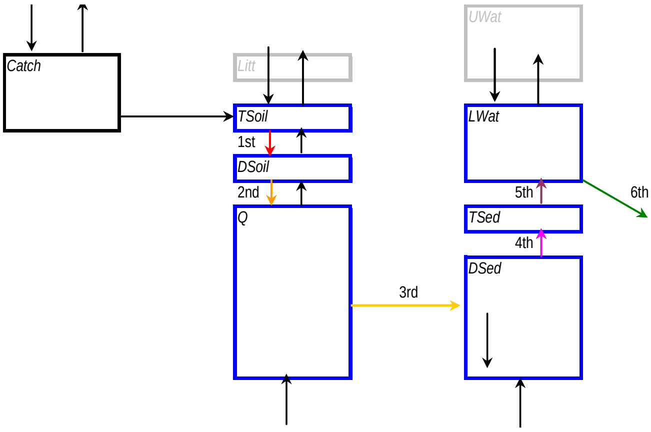
QD, soils, sediments $$\lambda_{ij} = \frac{1}{V_i} \cdot \frac{F_{ij} + k_i M_{ij}}{\theta_i + (1-\varepsilon_i)\rho_i k_i} \text{ y}^{-1}, \quad (2.3a)$$

Water bodies: $$\lambda_{ij} = \frac{F_{ij} + k_i M_{ij}}{V_i} \text{ y}^{-1}. \quad (2.3b)$$

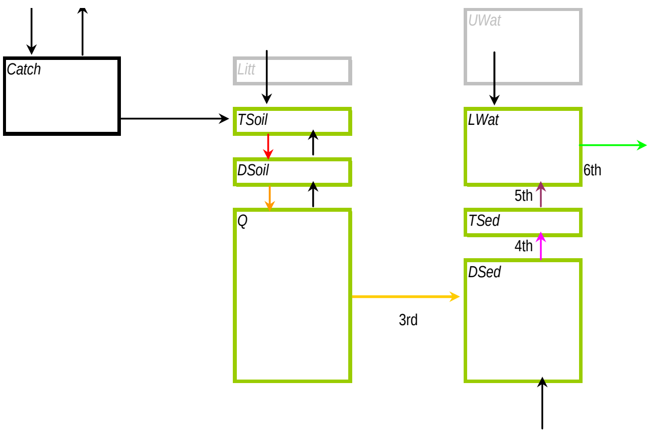
using the water and solid material fluxes of Figures 3.5 and 3.6 respectively combined with the following compartment k_d values (Table 3.7):

KLitt	Not used	m^3 kg^{-1}
KTSoil	0.5	m^3 kg^{-1}
KDSoil	7	m^3 kg^{-1}
KQ	7	m^3 kg^{-1}
KUWat	Not used	m^3 kg^{-1}
KLWat	10	m^3 kg^{-1}
KTSed	7	m^3 kg^{-1}
KDSed	7	m^3 kg^{-1}
lambda0	1.83E+00	y^{-1}

Time invariant compartment properties are given in Table 3.3 and the time varying parameters in Table 3.4. The leading diagonal of the matrix represents the sum of all losses (negative) from the compartment, including radioactive decay at the rate determined by the decay constant lambda0.



F_ATM_Catch	=	dppt*ACatch	=	6.14E+05
F_ATM_Lwat	=	dppt*ALWat	=	1.33E+02
F_ATM_Tsoil	=	dppt*ATsoil	=	2.65E+05
F_Catch_Tsoil	=	F_ATM_Catch-F_Catch_ATMOut	=	1.02E+05
F_Catch_ATMOut	=	dETp*ACatch	=	5.12E+05
F_Dsed_Tsed	=	F_GBI_Dsed+F_Q_Dsed	=	1.73E+05
F_Tsed_Lwat	=	F_Dsed_Tsed	=	1.73E+05
F_Lwat_ATMOut	=	dETp*ALWat	=	1.11E+02
F_Lwat_EcoOutflow	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut	=	1.73E+05
F_GBI_Q	=	AQ*vGBI*SIN(phiGBI)	=	2.61E+04
F_Q_Dsed	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q	=	1.73E+05
F_Q_Dsoil	=	dcapil*AQ	=	4.42E+04
F_Dsoil_Q	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil	=	1.91E+05
F_Dsoil_Tsoil	=	dcapil*ADSoil	=	4.42E+04
F_Tsoil_Dsoil	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut	=	1.91E+05
F_Tsoil_ATMOut	=	dETTSoil*ATsoil	=	2.21E+05



M_ATM_Lwat	=	mdep*ALWat	=	2.22E+00
M_ATM_Tsoil	=	mdep * ATsoil	=	4.42E+03
M_Catch_Tsoil	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil	=	1.02E+02
M_Dsed_Tsed	=	M_Q_Dsed+M_GBI_Dsed	=	4.55E+03
M_Tsed_Lwat	=	M_Dsed_Tsed	=	4.55E+03
M_Lwat_EcoOutflow	=	M_Tsed_Lwat+M_ATM_Lwat+M_Catch_Lwat	=	4.55E+03
M_GBI_Q	=	alphaQ*F_GBI_Q	=	2.61E+01
M_Q_Dsed	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q	=	4.55E+03
M_Q_Dsoil	=	alphaQ*F_Q_Dsoil	=	4.42E+01
M_Dsoil_Q	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil	=	4.57E+03
M_Dsoil_Tsoil	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil	=	8.85E+05
M_Tsoil_Dsoil	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil	=	8.89E+05

Figure 3.8. Water and solid material flux balance for the representation of agricultural soils with streams. Numerical values for northern Borholmsfjärden (LF2:01) at 5000 AD.

transfer matrix	Dsed	Tsed	Lwat	Uwat	Q	Dsoil	Tsoil	Litt	loss
Dsed	-2.18E+00	3.55E-01	0	0	0	0	0	0	0
Tsed	0	-3.07E+00	1.24E+00	0	0	0	0	0	0
Lwat	0	0	-4.92E+03	0	0	0	0	0	4.92E+03
Uwat	0	0	0	-1.83E+00	0	0	0	0	0
Q	5.57E-06	0	0	0	-1.83E+00	1.21E-06	0	0	0
Dsoil	0	0	0	0	7.76E-05	-1.83E+00	2.17E-03	0	0
Tsoil	0	0	0	0	0	1.80E-02	-1.85E+00	0	0
Litt	0	0	0	0	0	0	0	-1.83E+00	0
loss	0	0	0	0	0	0	0	0	-1.83E+00

Figure 3.9. GEMA transfer coefficients for ^{210}Po in the representation of northern Borholmsfjärden as agricultural land from 5000 to 10 000 AD. The values are calculated from

QD, soils, sediments $$\lambda_{ij} = \frac{1}{V_i} \cdot \frac{F_{ij} + k_i M_{ij}}{\theta_i + (1-\varepsilon_i)\rho_i k_i} \text{ y}^{-1}, \quad (2.3a)$$

Water bodies: $$\lambda_{ij} = \frac{F_{ij} + k_i M_{ij}}{V_i} \text{ y}^{-1}. \quad (2.3b)$$

using the water and solid material fluxes of Figure 3.8 respectively combined with the following compartment k_d values (Table 3.7):

KLitt	Not used	$m^3\ kg^{-1}$
KTSoil	0.5	$m^3\ kg^{-1}$
KDSoil	7	$m^3\ kg^{-1}$
KQ	7	$m^3\ kg^{-1}$
KUWat	Not used	$m^3\ kg^{-1}$
KLWat	10	$m^3\ kg^{-1}$
KTSed	7	$m^3\ kg^{-1}$
KDSed	7	$m^3\ kg^{-1}$
lambda0	1.83E+00	y^{-1}

Time invariant compartment properties are given in Table 3.3 and the time varying parameters in Table 3.4. The leading diagonal of the matrix represents the sum of all losses (negative) from the compartment, including radioactive decay at the rate determined by the decay constant lambda0.

Table 3.3. Time invariant parameters for LF2:01. These parameters are applicable to all ecosystem at all times.

Parameter		units	value	source
evapotranspiration	dETp	m y-1	0.5	Bergström & Barkefors (2004)
precipitation	dppt	m y-1	0.6	Bergström & Barkefors (2004)
mass deposition rate	mDep	kg m-2 y-1	0.01	Assumed value
erosion rate	mEros	kg m-2 y-1	0.01	Assumed value
groundwater velocity entering biosphere	vGBI	m y-1	0.058	SKB (2006c)
	phiGBI	rad	1.570796	Assumed vertical
capillary rise	dcapil	m y-1	0.1	Klos et al (1996)
active biomass	mDSoil	kg m-2	0.1	Klos et al (1996)
biomass activity	wDSoil	y-1	20	Klos et al (1996)
irrigation	dirri	m y-1	0	No irrigation
suspended solid load	alphaDSed	kg m-3	0.002	Assumed from Klos et al. (1996)
	alphaTSed	kg m-3	0.002	Assumed from Klos et al. (1996)
	alphaLWat	kg m-3	0.002	Assumed from Klos et al. (1996)
	alphaUWat	kg m-3	not used	
	alphaQ	kg m-3	0.001	Assumed from Klos et al. (1996)
	alphaDSoil	kg m-3	0.001	Assumed from Klos et al. (1996)
	alphaTSoil	kg m-3	0.001	Assumed from Klos et al. (1996)
	alphaLitt	kg m-3	not used	
compartment density*	RhoLWat	kg m-3	1000	
	RhoDSed	kg m-3	2650	Density of parent mineral
	RhoTSed	kg m-3	2650	
	RhoQ	kg m-3	2650	
	RhoDSoil	kg m-3	2650	
	RhoTSoil	kg m-3	2650	
	RhoLitt	kg m-3	2650	

* There is some debate about the use of density in the SR-Can models. The use of mineral density here means that bulk density can be readily expressed as

$$\rho_{bulk} = (1-\varepsilon)\rho_{mineral}$$

if the sample is dried. For a wet sample this might become

$$\rho_{bulk} = (1-\varepsilon)\rho_{mineral} + \theta\rho_{water}$$

might be used. The porosity of the medium is ε and volumetric moisture content θ.

The schematic water flux system in Figure 3.5 is valid for evolving bays, lakes and wetlands. There are difference in the representation of agricultural land. The compartments differ in size but primarily the stream carries suspended sediment load downstream. The mass balance scheme for agricultural land is shown in Figure 3.8. The structure is representative of other SAS ecosystems. In the case of WAS (see Table 3.2) the schemes shown in Figures 3.5 and 3.6 apply. The transfer matrix for ^{210}Po is shown in Figure 3.9

Many of the parameters in the model are not assumed to change in time. These are listed in Table 3.3. Details for the northern Borholmsfjärden system are given in Appendix E. Details of the other GEMA models are available from the author on request.

3.2.4 Time varying parameters

Volumes and areas change in time and these influence the water and solid material fluxes through the relations listed in Figures 3.5, 3.6 and 3.7. Using a step change regime to model system change means that the shape of the landscape objects illustrated in Figure 3.2 can be used to define the objects. Global Mapper (2007) has been used for this purpose. The procedure is as follows:

1. Determine the shape of the object based on the contour line at intervals defined by sea level fall each one thousand years (0 m, present day, -1 m 3000 AD, -2 m 4000 AD, etc.). GlobalMapper (2007) calculates the area within the current sea level contour.

2. The area of the emergent soil at each evolutionary stage is calculated from the difference of aquatic areas.

3. The volume of the water body is also determined by routines in GlobalMapper. Together with the area data, the depth of the water column is determined.

Bergström et al. (1999) is the source for the soil thicknesses and the depth of compartment Q is the difference in the thickness of the overall QD from the QD map and the deep and top soil depths. Bay, lake and wetland sediments are assumed to have a top sediment of 0.1 m, consistent with the data in Lindborg (2006). Streams are assumed to be 2 m wide and 20 cm deep based on observations of the model area. The depth of the top sediment is also 0.1 m and the deep sediment of streams is 0.2 m above the QD compartment. Characteristics of the soil are taken from Bergström et al. (1999) in terms of porosity. The degree of saturation is assumed. Details for northern Borholmsfjärden are summarised in Table 3.4.

Contaminant transport in the GEMA model is governed by the expression in Equation (2.1). The step change approach to evolution runs the model for each evolutionary system description and then changes the parameters to reflect the new state. There is a need to transfer activity between the compartments as a result of the evolutionary changes. Figure 3.4 illustrates the situation.

The bed sediment of the lake at 2000 AD accumulates activity. By 3000 AD some of the sediment now underlies soil: there is a net transfer from aquatic sediment to terrestrial soils and QD. In the SR-Can review this transfer is modelled using a transfer matrix **T** in the form

$$\mathbf{T} = \begin{pmatrix} f & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & f & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ (1-f)p_Q & (1-f)p_Q & 0 & 0 & 1 & 0 & 0 & 0 \\ (1-f)p_{DSoil} & (1-f)p_{DSoil} & 0 & 0 & 0 & 1 & 0 & 0 \\ (1-f)p_{TSoil} & (1-f)p_{TSoil} & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{3.2}$$

with $f = \dfrac{A_{LWat}|_k}{A_{LWat}|_{k-1}}$ and $p_i = \left.\dfrac{l_i|}{\sum\limits_{\substack{t=Q,DSed,\\TSed,Litt}} l_t}\right|_k$, where k denotes the evolutionary stage. This matrix takes the distribution of radionuclides in the vector of GEMA final inventories at the (k - 1)th step and calculates the initial inventories at the start of the next evolutionary phase:

$$\mathbf{N_k}\left(t_{ini}^{k}\right) = \mathbf{TN_k}\left(t_{fin}^{k-1}\right). \tag{3.3}$$

This is carried out prior to the evaluation of the model for the k^{th} stage of the ecosystem for each radionuclide. It is the function of the code element `Set_Fluxes.m` described in Appendix C.

3.2.5 Borholmsfjärden *extreme*: small bay north of Borholmsfjärden

The Borholmsfjärden object is part of the landscape system analysed in SR-Can (SKB, 2006a). As noted above alternative discretisations are possible. In modelling terms important objects are those of limited spatial extent which receive small volumes of uncontaminated mass fluxes with which the contaminant release can be diluted. The area identified in Figure 3.1 as *Borholmsfjärden extreme* is one such area. It's role in SR-Can is not clear, it being much smaller than the other landscape objects modelled therein. It does not appear to be connected to central Borholmsfjärden and could be part of another larger basin to the north of Borholmsfjärden. However, the map of the present day area shown in Figure 3.10 suggests that drainage would be to the north of central Borholmsfjärden.

Evolution of the BRH_x object can be interpreted as follows:

- 2000 – 3000 AD: shallow lake with natural soils emerging
- 3000 – 4000 AD: wetland with natural soils
- 4000 – 10000 AD: agricultural land with stream drainage.

Table 3.4. Time varying parameters for LF2:01 northern Borholmsfjärden. Data derived using Global Mapper (2007) from the SKB topographic and QD maps unless otherwise indicated. For streams the width is assumed to be 2 m.

Parameter		units	Date AD 2000 BCS	3000 LNS	4000 WNS	5000 SAS	source
Local catchment area	ACatch	m2	1024059.6	1024059.6	1024059.6	1024059.6	Derived
compartment areas	ADSed	m2	442534.4	297611.1	28105	222	Derived
	ATSed	m2	442534.4	297611.1	28105	222	Derived
	ALWat	m2	442534.4	297611.1	28105	222	Derived
	AUWat	m2	not used				
	AQ	m2	n/a	144923.3	414429.4	442312.4	Derived
	ADSoil	m2	n/a	144923.3	414429.4	442312.4	Derived
	ATSoil	m2	n/a	144923.3	414429.4	442312.4	Derived
	ALitt	m2	not used				
compartment volumes	VDSed	m3	3230501.12	2172561.03	205166.5	44.4	Derived
	VTSed	m3	44253.44	29761.11	2810.5	22.2	Derived
	VLWat	m3	452181.6219	155708.8249	7479.85	44.4	Derived
	VUWat	m3	not used				
	VQ	m3	n/a	1036201.595	2963170.21	2830799.36	Derived
	VDSoil	m3	n/a	21738.495	62164.41	309618.68	Derived
	VTSoil	m3	n/a	14492.33	41442.94	132693.72	Derived
	VLitt	m3	not used				
compartment thicknesses	LDSed	m	7.3	7.3	7.3	0.2	Assumed
	LTSed	m	0.1	0.1	0.1	0.1	Assumed
	LLWat	m	1.021799937	0.523195623	0.266139477	0.2	Derived
	LUWat	m	not used				
	LQ	m	n/a	7.15	7.15	6.4	Derived
	LDSoil	m	n/a	0.15	0.15	0.7	Bergström et al. 1999
	LTSoil	m	n/a	0.1	0.1	0.3	Bergström et al. 1999
	LLitt	m	not used				
compartment porosity	EpsDSed	-	0.3	0.3	0.3	0.3	Bergström et al. 1999
	EpsTSed	-	0.6	0.6	0.6	0.6	Bergström et al. 1999
	EpsQ	-	n/a	0.3	0.3	0.3	Bergström et al. 1999
	EpsDSoil	-	n/a	0.3	0.3	0.5	Bergström et al. 1999
	EpsTSoil	-	n/a	0.3	0.3	0.8	Bergström et al. 1999
	EpsLitt	-	not used				
compartment volumetric moisture content	ThetaDSed	-	0.3	0.3	0.3	0.3	Saturated
	ThetaTSed	-	0.6	0.6	0.6	0.6	Saturated
	ThetaQ	-	n/a	0.3	0.3	0.3	Saturated
	ThetaDSoil	-	n/a	0.3	0.3	0.5	Saturated
	ThetaTSoil	-	n/a	0.3	0.25	0.6	Assumed
	ThetaLitt	-	not used				

Table 3.5. Time varying parameters for BRH_x Borholmsfjärden extreme. Data derived using Global Mapper (2007) from the SKB topographic and QD maps. For streams the width is assumed to be 2 m.

Parameter		units	Date AD 2000 LNS	3000 WNS	4000 SAS	source
Local catchment area	ACatch	m2	36341	36341	36341	Derived
compartment areas	ADSed	m2	16731	3099	115	Derived
	ATSed	m2	16731	3099	115	Derived
	ALWat	m2	16731	3099	115	Derived
	AUWat	m2	not used			
	AQ	m2	0	13632	16616	Derived
	ADSoil	m2	0	13632	16616	Derived
	ATSoil	m2	0	13632	16616	Derived
	ALitt	m2	not used			
compartment volumes	VDSed	m3	122136.3	22622.7	23	Derived
	VTSed	m3	1673.1	309.9	11.5	Derived
	VLWat	m3	4445.6618	619.8	11.5	Derived
	VUWat	m3	not used			
	VQ	m3	0	97468.8	106342.4	Derived
	VDSoil	m3	0	2044.8	11631.2	Derived
	VTSoil	m3	0	1363.2	4984.8	Derived
	VLitt	m3	not used			
compartment thicknesses	LDSed	m	7.3	7.30E+00	2.00E-01	Assumed
	LTSed	m	0.1	1.00E-01	1.00E-01	Assumed
	LLWat	m	0.26571405	2.00E-01	1.00E-01	Derived
	LUWat	m	not used			
	LQ	m	7.15	7.15	6.4	Derived
	LDSoil	m	0.15	0.15	0.7	Bergström et al. 1999
	LTSoil	m	0.1	0.1	0.3	Bergström et al. 1999
	LLitt	m	not used			
compartment porosity	EpsDSed	-	0.3	0.3	0.3	Bergström et al. 1999
	EpsTSed	-	0.6	0.6	0.6	Bergström et al. 1999
	EpsQ	-	0.3	0.3	0.3	Bergström et al. 1999
	EpsDSoil	-	0.3	0.3	0.5	Bergström et al. 1999
	EpsTSoil	-	0.3	0.3	0.8	Bergström et al. 1999
	EpsLitt	-	not used			
compartment volumetric moisture content	ThetaDSed	-	0.3	0.3	0.3	Saturated
	ThetaTSed	-	0.6	0.6	0.6	Saturated
	ThetaQ	-	0.3	0.3	0.3	Saturated
	ThetaDSoil	-	0.3	0.3	0.5	Saturated
	ThetaTSoil	-	0.3	0.25	0.6	Assumed
	ThetaLitt	-	not used			

Figure 3.10. Composite map of the small isolated catchment northeast of Borholmsfjärden (GlobalMapper, 2007 using topographic data from Lindborg, 2006 combined with fitted GoogleEarth image). This shallow lake has formed recently as a result of the retreat of the Baltic. There are smaller water bodies to the north but the release points (SKB, 2006a) indicate the main area of interest is as shown. Contours at 0.25 m intervals indicate sea-level at 250 y steps suggesting that the indicated area will become isolated in the short term forming first a wetland (assumed to be 3000 AD) and then being drained for agricultural production (from 4000 AD onwards).

With this classification the structure of the models for LF2:01 can be used, starting with the LNS system and progressing to WNS and finally SAS. The mass balance schemes for LF2:01 can therefore be translated for BRH_x. The difference is in terms of the size of the object and depth of water. Time invariant parameters for Borholmsfjärden *extreme* are the same as for other parts of the Laxemar region (Table 3.3) and those time varying parameters which differ from LF2:01 are given in Table 3.5.

As can be seen in the comparison of Tables 3.4 and 3.5, BRH_x is significantly smaller than LF2:01. Corresponding numerical data for water, solid and contaminant fluxes are given in Appendix E.

Avila et al. (2006) discusses the population sizes supported by different ecosystem types. Wetlands have the lowest productivity and so during lake/wetland phases BRH_x could not support a significant human population. The TFagg approach in SR-Can (SKB, 2006a) explicitly takes this into account whereas the total dose over all pathways in GEMA does not. However, the agricultural area of BRH_x could support up to 30 adults.

3.3 An extended landscape model: Lake Bolundsfjärden, Forsmark

3.3.1 GEMA flowpath elements in the Bolundsfjärden catchment

The final GEMA example is of an extended landscape based on a preliminary model of the biosphere around Lake Bolundsfjärden at Forsmark at 2000 AD. Based on a preliminary distribution of potential release locations provided by Marklund (2005). Figure 3.11 illustrates the entire system with the GEMA modules associated with the release locations and the drainage system indicated by the shaded squares.

This proof-of-concept implementation comprises a large number of distinct GEMA modules in the drainage system, identified by flowpath and element within the system. As with the releases estimated by SKB in SR-Can there are numerous potential release locations, with Lake Bolundsfjärden at the centre. Ultimately releases flow to Öregrundsgrepen to the north.

To illustrate contaminant migration through the modelled landscape the focus here is on the release to flowpath element F1:01 to the south-west near to Gällsboträsket. The elements of the drainage system considered in the model are illustrated in Figure 3.12. Only radionuclide transport is considered in the results discussed in Section 4.2 and the system characteristics are not assumed to change in time.

3.3.2 Data description

Interpretation of the surface drainage system in the Bolundsfjärden catchment is based on the stream network in the contour map of the area in (Lindborg, 2005; Appendix 1). The flowpath elements are labelled F1 to F11 and individual sections of these are identified on the basis of the hydrological boundaries in the system. A new section is modelled where, for example, there is a confluence so that the characteristics of the water body would be expected to change. This accounts for the many elements of the flowpath. A more sophisticated interpretation of the site would be likely to employ fewer flowpath elements.

In this preliminary model a simple interpretation of topographic map was used to determine the size of objects and their arrangement in the flowpath. Physical characteristics, e.g., porosity, were taken from the discussions in (Lindborg 2005) and the local climate characteristics are also taken from the discussion of local meteorological data (Lindborg 2005; 2006). These are broadly similar to the values used in the model detailed models of the ecosystems in the Laxemar system discussed above.

Nuclide hydrogeochemistry is based on the same classification of ecosystem types as for the Laxemar models. The numerical data for these are given in Section 3.4.

Simple mass balance schemes are employed for the objects in the Bolundsfjärden drainage system. Release is assumed to be to the Q compartment of element F1:01. Subsequent transport is predominantly in the water column of streams and lakes. Details of the F1:01 fluxes are given in Figure 3.13 and basic landscape characteristics shown in Table 3.6. Further numerical details for F1:01 are presented in Appendix E.

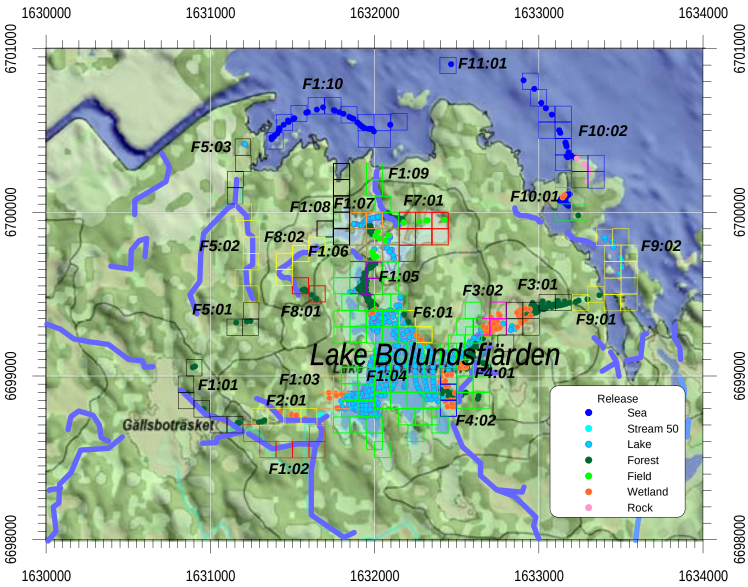


Figure 3.11. Location of GEMA flowpath elements for the preliminary model of the model of Forsmark in the present day. Release points and receiving ecosystem type are provided by Marklund (2005), topographic map taken from Lindborg (2005). Streams are shown as blue lines. GEMA modules are constructed on a 50 m grid along the flow system towards discharge in the Baltic.

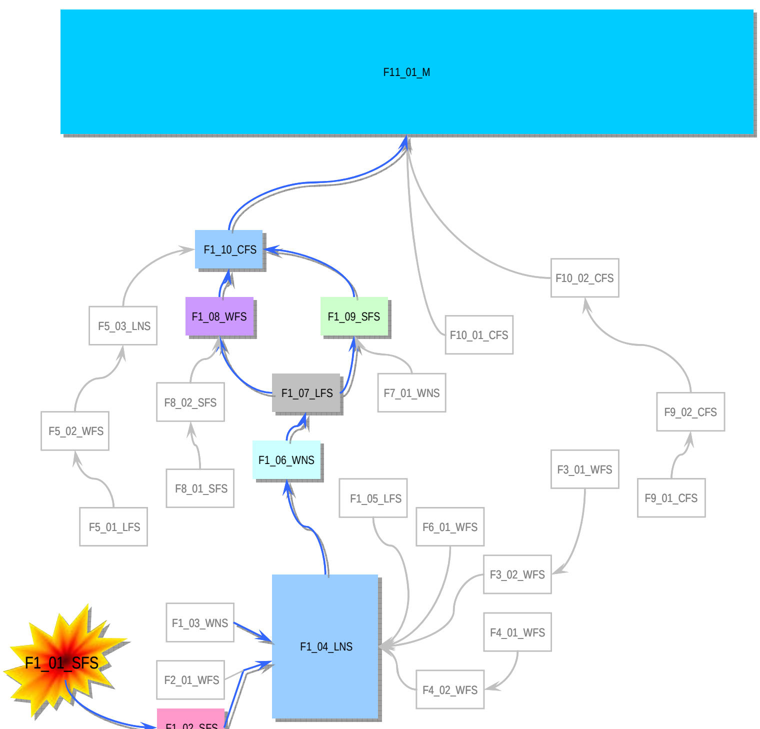
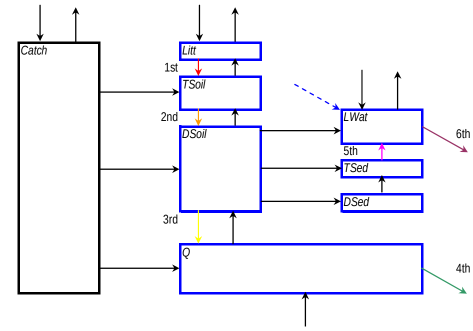


Figure 3.12. Schematic overview of the contaminant flow network. The flow path for a release to flowpath element F1:01 is indicated.

Water fluxes:



Solid material fluxes:

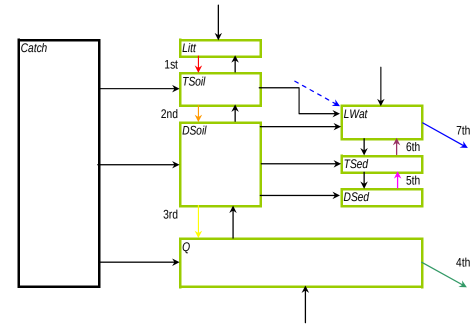


Figure 3.13. Water and solid material fluxes in the F1:01 element of the Bolundsfjärden catchment model. The model is time invariant, featuring a stream with forest (cf. natural) soils.

Table 3.6. Basic data for the Bolundsfjärden catchment drainage system. Many streams in the area are small with limited flow. In this approximation small volumes were used to represent this fact. Predominant flow in such cases is subsurface.

Flowpath element	ecosystem type	catchment area [m²]	water area [m²]	water depth [m]	soil area [m²]
F1:01	SFS – stream, forest soils	120000	200	0.01	60000
F1:02	SFS – stream, forest soils	100000	300	0.01	140000
Lake Bolundsfjärden F1:04	LNS – lake, natural soils	2890000	610000	0.61	15000
F1:06	WNS – wetland, natural soils	60000	27500	0.1	22500
F1:07	LFS – lake, forest soils	0	12500	1	7500
F1:08	WFS – wetland, forest soils	50000	25000	0.1	35000
F1:09	SFS – stream, forest soils	45000	800	0.01	29600
F1:10	CFS – coast, forest soils	0	2000000	1.5	2500
Öregrundsgrepen F1:11	M – marine	0	610000	10.2	-

precipitation	0.6 m y^{-1}
ETp	0.5m y^{-1}

3.4 Nuclide specific data

Radionuclide details are specified for each of the ecosystem models as a function of time. In the SR-Can model the database from Karlsson & Bergström (2002) was used and these are the data employed here. The k_d values are categorised as shown in Table 3.7 which illustrates how the ecosystem types for the Laxemar bays are described as a function of time.

Nine radionuclides are included in the Xu et al. (2008) review: ^{36}Cl, ^{59}Ni, ^{79}Se, ^{99}Tc, ^{129}I, ^{135}Cs, and the members of the ^{226}Ra chain: ^{226}Ra, ^{210}Pb and ^{210}Po. The other radionuclide specific data (non-ecosystem dependent) are shown in Tables 3.6 to 3.8.

3.5 Exposure groups

The dietary and intake parameters assumed for the model are given in Table 3.11. Each of the ecosystem types has its own set of pathways assumed to be consumed. These are effectively switches used to control whether or not the pathway is included in the GEMA calculation. Fractional rates could be assumed in the case where some dilution with uncontaminated material was deemed necessary. Additionally a value higher than unity could be set to represent increased consumption. These data are included in the main GEMA definition of the ecosystem.

In GEMA active pathways can be configured for each of the ecosystem types. Table 3.12 illustrates those assumed for the Laxemar and Forsmark regions focussing on the ecosystems used in the examples. For the marine case only marine fish are assumed. In the case of freshwater lakes freshwater fish, invertebrates and the game pathway are active. Associated natural soils are a source of nuts, fruits and mushrooms. Wetlands are similar but are not assumed to be suitable for fish though game animals still consume surface water. Agricultural foodstuffs are part of the diet during agricultural conditions. A well in the QD is assumed to be the source of drinking water for humans. Game and livestock consume from the surface water body. When there are contaminated soil compartments, full occupancy is assumed for dust inhalation, external irradiation and soil ingestion.

This format provides the flexibility to customise the application according to the societal context of assessment.

Table 3.7. Solid – liquid distribution coefficients [m³ kg⁻¹] Karlsson & Bergström (2002) specify k_ds for the classifications “soil”, “organic”, “brackish” and “lake”. This table shows the values for each of these types as well as the category assigned to the ecosystem types in the model of the Laxemar bays.

nuclide	Half life y	Soil $m^3\ kg^{-1}$	Organic Soil $m^3\ kg^{-1}$	susp solids lakes $m^3\ kg^{-1}$	susp solids brackish water $m^3\ kg^{-1}$
36Cl	301000	0.001	0.01	1	0.001
59Ni	76000	0.5	1	10	10
79Se	1130000	0.01	2	5	5
99Tc	211000	0.005	0.002	0.1	0.1
129I	15700000	0.3	0.03	0.3	0.3
135Cs	2300000	1	0.3	10	10
226Ra	1600	0.5	2	10	10
210Pb	22.3	0.1	20	0.05	0.05
210Po	0.37891647	0.5	7	10	20

GEMA compartment	BCS	LNS	WNS	SAS	WAS
KLitt	-	-	-	-	-
KTSoil	organic	organic	organic	soil	soil
KDSoil	organic	organic	organic	organic	organic
KQ	organic	organic	organic	organic	organic
KUWat	-	-	-	-	-
KLWat	brackish	lake	lake	lake	lake
KTSed	organic	organic	organic	organic	organic
KDSed	organic	organic	organic	organic	organic

key	Aquatic	Terrestrial
BCS	Bay	Coastal / Natural soils
LNS	Lake	Natural soils
WNS	Wetland	Natural soils
WAS	Wetland	Agricultural soils
SAS	Streams	Agricultural soils

Table 3.8. Soil – plant transfer factors Karlsson & Bergström (2002), except *, IAEA (2003) and **, Kłos & Albrecht (2005).

nuclide	pasture Bq kg^{-1} (fw) (Bq m-3)$^{-1}$	cereals Bq kg^{-1} (fw) (Bq m-3)$^{-1}$	root crops Bq kg^{-1} (fw) (Bq m-3)$^{-1}$	vegetables Bq kg^{-1} (fw) (Bq m-3)$^{-1}$	Trans-location m^2 kg^{-1}	wild fruit* Bq kg^{-1} (fw) (Bq m-3)$^{-1}$	nuts* Bq kg^{-1} (fw) (Bq m-3)$^{-1}$	fungi* Bq kg^{-1} (fw) (Bq m-3)$^{-1}$
^{36}Cl	30	30	6	3	0.1	30	30	30
^{59}Ni	0.2	0.03	0.04	0.02	0.01	0.025	0.025	0.164
^{79}Se	20	20	4	2	0.1	0.2	0.2	0.2
^{99}Tc	8	0.6	0.05	20	0.005	11	11	78
^{129}I	0.6	0.1	0.01	0.03	0.1	0.0003	0.0003	0.0003
^{135}Cs	0.2	0.02	0.02	0.02	0.2	0.014	0.014	0.02
^{226}Ra	0.08	0.001	0.004	0.005	0.1	0.0005**	0.005**	0.02**
^{210}Pb	0.001	0.004	0.004	0.001	0.03	0.0005**	0.005**	0.02**
^{210}Po	0.05	0.001	0.004	0.001	0.1	0.0005**	0.005**	0.02**

Table 3.9. Uptake factors for fauna (Karlsson & Bergström 2002):

nuclide	fw fish m^3 kg^{-1}	Baltic fish m^3 kg^{-1}	fw inv. m^3 kg^{-1}	milk day m^{-3}	meat day m^{-3}
^{36}Cl	0.05	0.001	0.1	0.017	0.02
^{59}Ni	0.1	0.3	0.1	0.02	0.005
^{79}Se	2	4	0.2	0.004	0.015
^{99}Tc	0.02	0.03	0.005	0.00002	0.0001
^{129}I	0.2	0.03	0.005	0.01	0.04
^{135}Cs	10	0.2	0.1	0.008	0.05
^{226}Ra	0.05	0.05	0.3	0.0013	0.0009
^{210}Pb	0.3	0.1	0.1	0.0003	0.0004
^{210}Po	0.05	2	20	0.00034	0.005

Table 3.10. Dose per unit exposure (Karlsson & Bergström 2002):

nuclide	external (Sv h^{-1})(Bq m^{-3})$^{-1}$	ingestion Sv Bq^{-1}	inhalation Sv Bq^{-1}
^{36}Cl	0	9.3×10^{-10}	7.3×10^{-9}
^{59}Ni	0	6.3×10^{-11}	4.4×10^{-10}
^{79}Se	0	2.9×10^{-9}	6.8×10^{-9}
^{99}Tc	0	6.4×10^{-10}	1.3×10^{-8}
^{129}I	3.4×10^{-16}	1.1×10^{-7}	3.6×10^{-8}
^{135}Cs	0	2×10^{-9}	8.6×10^{-9}
^{226}Ra	6×10^{-16}	2.8×10^{-7}	9.5×10^{-6}
^{210}Pb	7.2×10^{-17}	6.9×10^{-7}	5.6×10^{-6}
^{210}Po	0	1.2×10^{-6}	4.3×10^{-6}

Table 3.11. Dietary intakes used in the GEMA calculations.

Human intake				
Parameter		Value	Units	Source
Water consumption	*Iwater*	0.6	$m^3\ y^{-1}$	Karlsson, Bergström & Meili (2001)
Fish consumption	*Ifish*	30	$kg\ y^{-1}$	
Meat consumption	*Ibeef*	70	$kg\ y^{-1}$	
Milk consumption	*Imilk*	0.3	$m^3\ y^{-1}$	
Game consumption	*Igame*	17.5	$kg\ y^{-1}$	
Fresh water invertebrate cons.	*Ifwinv*	2	$kg\ y^{-1}$	
Green veg. consumption	*Iveg*	60	$kg\ y^{-1}$	
Root veg. consumption	*Iroot*	70	$kg\ y^{-1}$	
Cereal consumption	*Icereals*	80	$kg\ y^{-1}$	
Soil ingestion	*Isoil*	0.1	$kg\ y^{-1}$	
Annual breathing rate	*Iair*	1.0	$m^3\ y^{-1}$	
Wild fruit consumption	*Iwfruit*	45	$kg\ y^{-1}$	Wörman et al., 2004
Nuts consumption	*Inuts*	1.5	$kg\ y^{-1}$	
Fungi consumption	*Ifungi*	6	$kg\ y^{-1}$	
Airborne dust load	*alphaAir*	1.0×10^{-4}	$kg\ m^{-3}$	Karlsson, Bergström & Meili (2001)
Occupancy factor	*OccF*	1.0	$year\ year^{-1}$	Full occupancy assumed

Animal intake				
Parameter		Value	Units	Source
Livestock				
Cattle daily intake	Icowpasture	8.5	$kg\ day^{-1}$	Karlsson, Bergström & Meili (2001)
Daily cattle soil intake	Icowsoil	0.3	$kg\ day^{-1}$	
Cattle intake of aquatic plants	Icowaqplants	8.5	$kg\ day^{-1}$	
Cow daily water intake	Icowwater	0.07	$m^3\ day^{-1}$	
Cattle cereal intake	Icereal	11	$kg\ day^{-1}$	
Game animals				
	Igamewfruit	9.75	$kg\ day^{-1}$	Wörman et al., (2004)
	Igamenuts	9.75	$kg\ day^{-1}$	
	Igamewater	0.3	$m^3\ day^{-1}$	
	Igamesoil	0.3	$kg\ day^{-1}$	

Table 3.12. Consumption pathways in the GEMA model of northern Borholmsfjärden. Active pathways for a given ecosystem are set to 1. Inactive are turned off with 0. For marine pathways only marine fish are considered. Well water is assumed for agricultural soils only. The source is an aquifer in the QD. Agricultural soils are assumed to be the source for most types of crops and foodstuffs.

	BCS	LNS	WNS	WAS	SAS
fDwater	0	0	0	0	0
fDwell	0	0	0	0	1
fDfwfish	0	1	0	0	1
fDmfish	1	0	0	0	0
fDfwinv	0	1	0	1	1
fDwfruit	0	1	1	1	1
fDnuts	0	1	1	1	1
fDfungi	0	1	1	1	1
fDbeef	0	0	0	1	1
fDmilk	0	0	0	1	1
fDgame	0	1	1	1	1
fDveg	0	0	0	1	1
fDroot	0	0	0	1	1
fDcereals	0	0	0	1	1
fDdust	0	1	1	1	1
fDext	0	1	1	1	1
fDSoil	0	1	1	1	1

4 ILLUSTRATIVE RESULTS

4.1 Evolving bays at Laxemar – modelling transitions

This first set of results illustrate how system change is implemented in GEMA. The system modelled is an evolving bay → lake → wetland → agricultural land sequence in northern Borholmsfjärden described in Section 3.2. System change is modelled as a sequence of discrete steps. Releases to two objects are presented:

- LF2:01 – northern Borholmsfjärden,
- BRH_x – a small isolated catchment to the northeast of Borholmsfjärden..

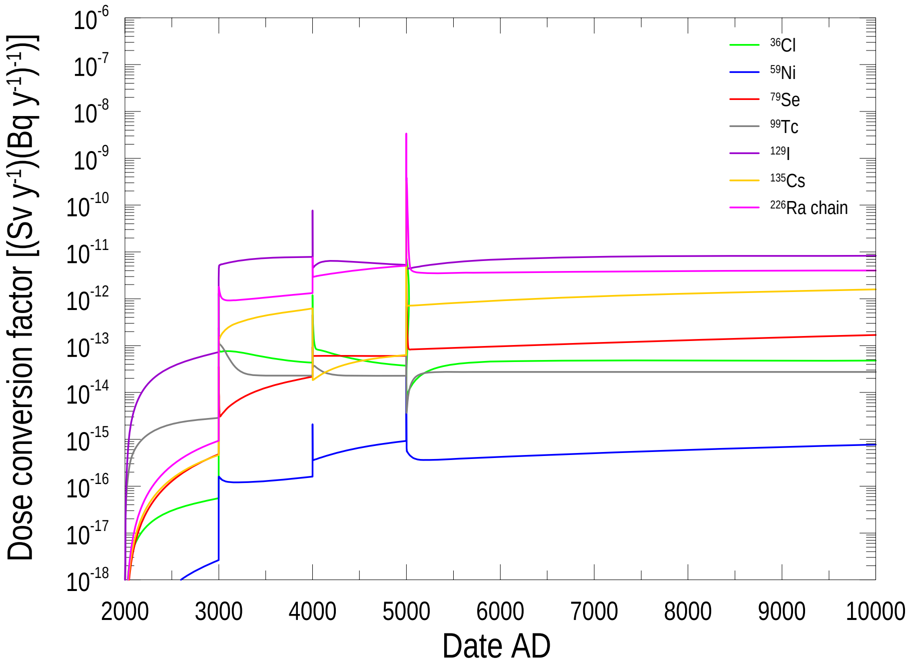
These two objects are distinguished by their respective sizes (see Figure 3.1) but both are radiologically significant in that they are potential release locations and are isolated from the main drainage system since they have no upstream catchment area contributing a diluting through-flow. Dilution is therefore governed only by the size of the local catchment.

GEMA's purpose is to calculate radiological consequences, primarily the dose per unit release, for radionuclide released to a set of flowpath elements. Example dose results for the radionuclides discussed above are shown in Figure 4.1. The doses are summed over each of the pathways according to the active pathways shown in Table 3.12.

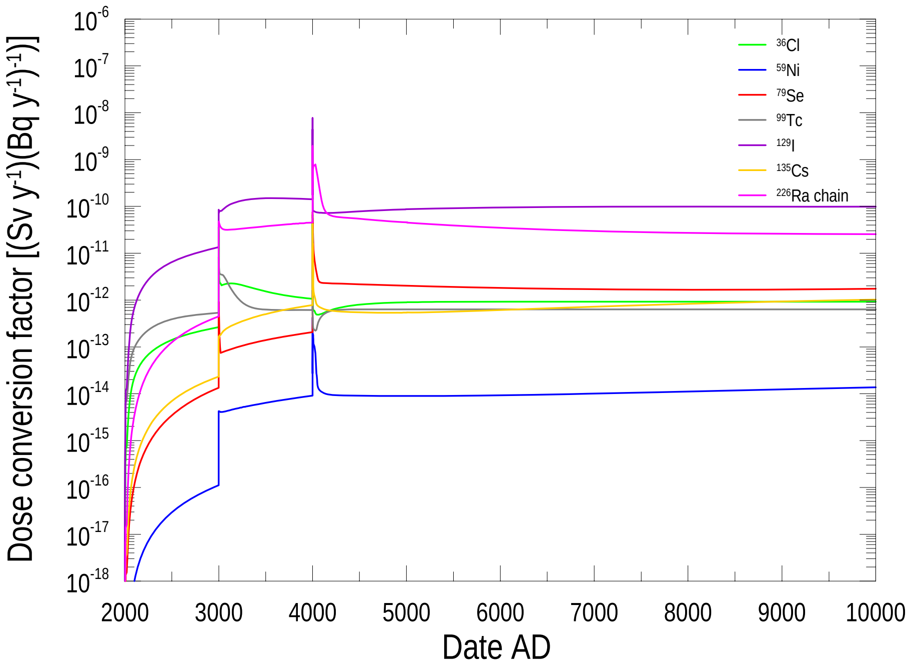
Doses are shown for the two GEMA flowpath elements described in Section 3.2. As might be expected, the smaller object gives the highest dose per unit release but most noticeable are the transients seen at the step changes of ecosystem type. Neglecting the spikes, the longer term doses calculated for LF2:01 are broadly comparable to the Landscape Dose Factors (LDFs) calculated for Laxemar by Avila et al. (2006). However, the longer term results for BRH_x are higher than the LDFs in SR-Can as a consequence of the smaller area and the limiting hydrology of Borholmsfjärden *extreme* object.

The nature of the transients is directly linked to the way in which system change is implemented. At issue is the way in which the compartment inventories calculated at the earlier evolutionary phase are partitioned at the transition via Equation (3.2). In reality the change between bay, lake and wetland states is likely to be gradual and this step-change format is not wholly accurate. Nevertheless, long term results are representative of a more realistic approximation. Furthermore, the transition from wetland with natural soils to stream-drained agricultural land is governed by human actions, specifically the short duration act of draining the wetland to form agricultural soils. As yet there is no way of addressing these issues on the basis of the site characterisation carried out by SKB. This first approximation to modelling step-transitions is therefore of interest.

The results illustrated here address, albeit briefly, the nature of the dynamics of the step change transition from wetland to agricultural land. The results for the ^{226}Ra chain show the effect to best advantage because of the higher k_ds of these elements, emphasising retention in soils and sediments. The ^{226}Ra chain also has the highest dose per unit release of all of the radionuclides modelled in the GEMA implementation of the Laxemar bays. ^{210}Po gives the highest dose of the three nuclides modelled in the release of ^{226}Ra.

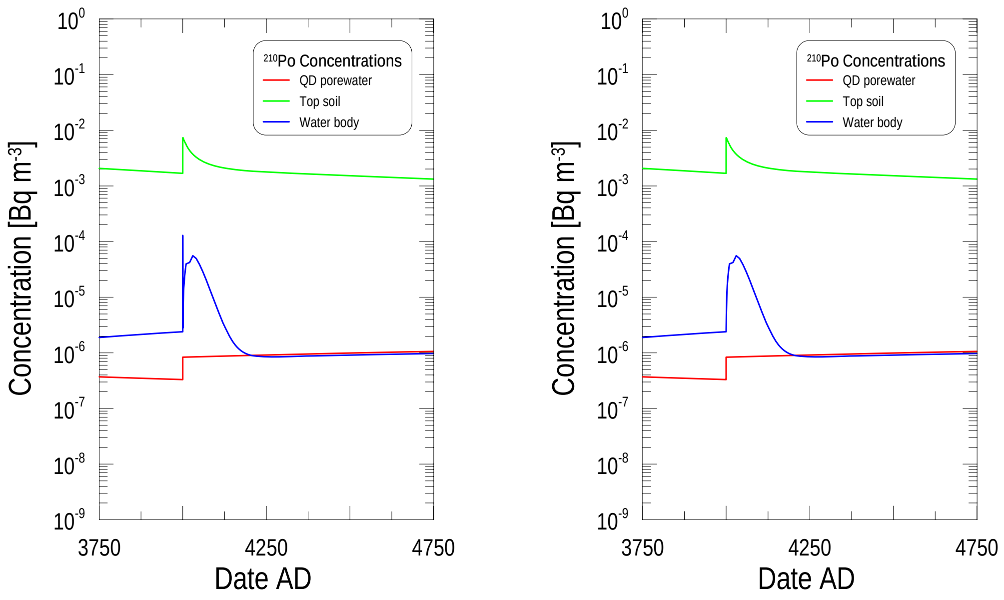


(a) Northern Borholmsfjärden, (LF2:01)



(b) Small isolated catchment – Borholmsfjärden *extreme* (BRH_x)

Figure 4.1. Example dose per unit release for two evolving systems at Laxemar starting at 2000 AD.



(a) times around the transition to agricultural land at 4000 AD default transition matrix – Equation (3.2).

(b) times around the transition to agricultural land at 4000 AD, alternate transition matrix – Equation (4.1).

Figure 4.2. Transient dynamics of the ^{210}Po inventories in the water column, top soil and QD porewater. Results for alternate approximations to the transition matrix are shown. The results indicate that the nature of the hydrological assumptions after the transition are important in determining radiological consequence.

The calculated doses depend on the radionuclide concentrations in QD porewater, water body and top soil compartments. These concentrations are plotted in Figure 4.2 for the BRH_x object around the transition to agricultural land at 4000 AD. During the wetland period from 3000 AD to 4000 AD the soils of the wetland are a significant source of potential exposure as a result of terrestrial development. On the change to agricultural land, where well water is used by humans and livestock, there is around a factor of three increase in the concentration in well water (the QD porewater).

Following the transition to agricultural land (with modification to local hydrology), there is an increase in the water concentration. At first sight this is is a consequence of the assumption that all of the water inventory in the wetland phase passes to the water column of the smaller stream that is assumed to have been constructed as the principle means of draining the catchment. This is seen in Figure 4.2 (a). However the dynamics of the water column concentration in the immediate aftermath of the change to the system indicate that a short duration high concentration pulse is also present. This can be confirmed by modifying the transition matrix from the form in Equation (3.2) to read

$$\mathbf{T} = \begin{pmatrix} f & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & f & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & r_{LWat} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ (1-f)p_Q & (1-f)p_Q & 0 & 0 & 1 & 0 & 0 & 0 \\ (1-f)p_{DSoil} & (1-f)p_{DSoil} & 0 & 0 & 0 & 1 & 0 & 0 \\ (1-f)p_{TSoil} & (1-f)p_{TSoil} & 1-r_{LWat} & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{4.1}$$

where, now, the factor r_{LWat} comes from the ratio of water object volumes before and after the transition:

$$r_{LWat} = \frac{V_{LWat}\big|_{t=4000}}{V_{LWat}\big|_{t=3000}} . \tag{4.2}$$

The transient for this is shown in Figure 4.2 (b).

In this interpretation the water volume is rapidly reduced by drainage such that the bulk of the wetland drains *through* the top soil. The inventory in LWat therefore reduces accordingly so that the concentration in the water columns is continuous across the transition. However, the water concentration does rise shortly after the transition as the new hydrological regime leaches activity from the soils back to the surface water column.

Neither top soil nor QD well concentrations are affected by this alternate assumption and, because of the effect of the high k_d of ^{210}Po, this model suggests that attention should focus on the recycling of contaminants from the top soil to the water column where the dose pathways involving the consumption of stream water by livestock and game are important.

The overall effect on dose is small for the members of the ^{226}Ra chain. The dose from the gradual increase in the water concentration via the flow through soil is only a factor of three lower when Equation (4.1) is used. There is reason to believe that doses from the BRH_x case could be as high as 10^{-9} Sv Bq^{-1} for the ^{226}Ra chain. Using the interpretation modelled here the top soil concentration arising from the evolution of wetland bed sediment to top soil can lead to a factor or ten increase in dose for a short duration.

The active FEPs here involve radionuclide fluxes through the soil column with return to the water column. Even for ^{129}I this can be important. The modified transition matrix reduces doses but only by a factor of 1.72. Alternative interpretations are important and there is a clearly demonstrated need to investigate alternative options for modelling transitions to a level of detail hitherto not appreciated.

t = 1 y

t = 10 y

t = 100 y

t = 1000 y

t = 10000 y

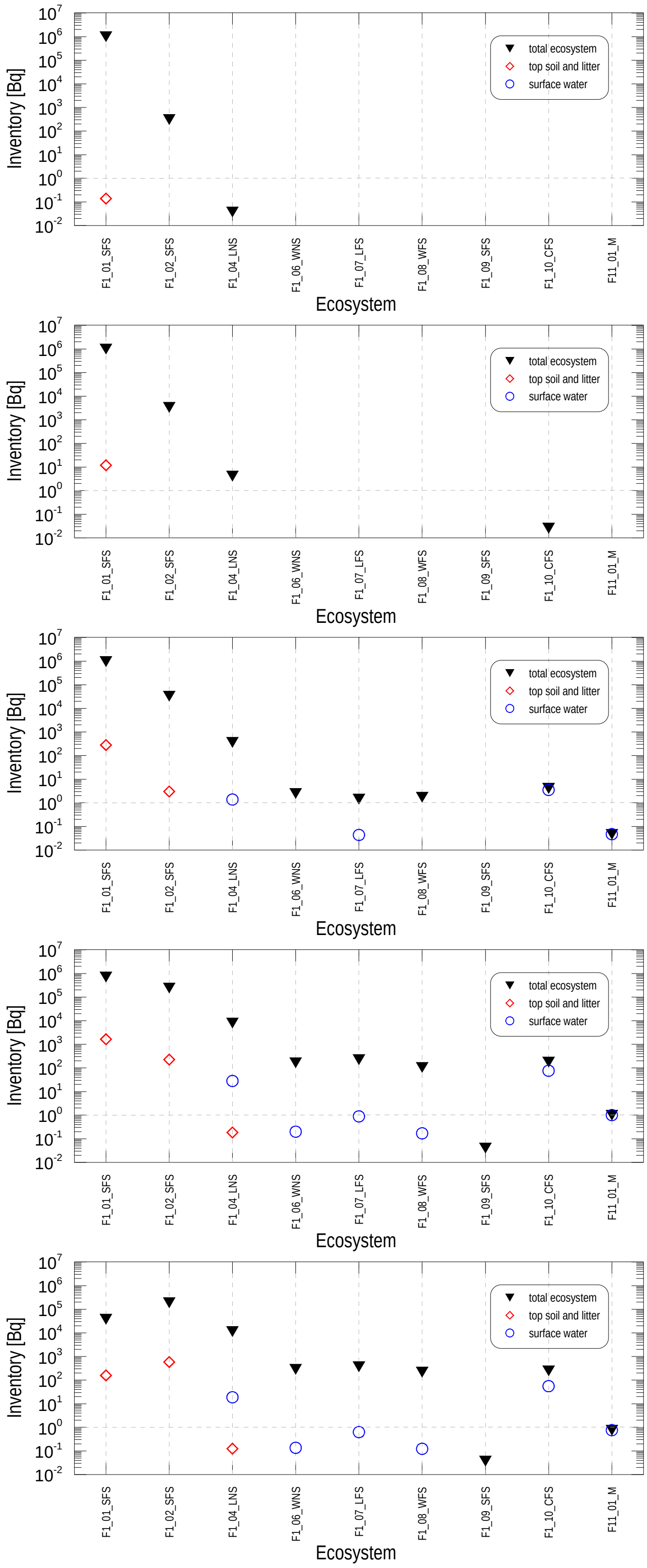


Figure 4.3. Distribution of activity along the flowpath at different times.

4.2 Contaminant fate in the Bolundsfjärden drainage system

The second set of results illustrate contaminant transport through a constant landscape. There are two contrasting features: transport along the drainage system and retention in the QD, illustrating the role played by the QD in ecosystem models.

Release locations in the preliminary Forsmark model (Section 3.3) are based on an interpretation of groundwater flow in the bedrock and QD as calculated as part of the early CLIMB groundwater modelling development by Marklund (2005). Although these data have since been superseded the release map illustrates how the GEMA modules can be assembled to represent a drainage system in the landscape. The network of flowpath elements corresponding to Figure 3.11 is shown in Figure 3.12. The model illustrates the fate of contaminants released to a small forested area to the west of Lake Bolundsfjärden.

Flow through flowpath F1 is linear until F1:07 where the available data suggests that there is flow to two downstream objects F1:08 and F1:09. Subsequently these two objects flow into F1:10. This bifurcation of fluxes and confluence are options in the GEMA landscape model. Ultimately all terrestrial hydrology flows to the Baltic to the north-northeast of the map.

To illustrate the functioning of the landscape model in GEMA this example considers the release of a pulse of 1 MBq y^{-1} of ^{129}I to the F1:01 ecosystem (centred at (1631000, 6698850) on the map) at time $t = 0$. This is the only release location and the fate of the release contaminants over a 10 ka period is illustrated in Figure 4.3. The topography of the release is such that the release is to the QD underlying the stream .

The ^{129}I k_d in the QD of F1:01 is 0.3 m^3 kg^{-1} and which is sufficient for the initial inventory of ^{129}I to remain mostly within the first flowpath element. This is because there is limited interaction of the QD with the stream water. Not until 2000 years have passed does the amount of activity lost downstream exceed the amount retained. A similar pattern is seen in F1:02 but there is a gradual increase of inventory in the QD compartment of the second module since the QD → QD transfer downstream from F1:01 to F1:02 dominates the losses from F1:01 and constitutes a dynamic "source term" to the QD of F1:02.

F1:02 flows into Lake Bolundsfjärden, again primarily in the subsurface hydrology of the QD. Once in the F1:04 module there is, according to this preliminary interpretation of the hydrogeology, relatively rapid transfer to the lower water compartment of the lake. From there the flows are fairly rapid downstream. The size of Lake Bolundsfjärden is such that it has the highest water inventory of any of the ecosystems' water columns. Given the nature of F1:06, F1:07 and F1:08 equilibrium is rapidly established and the contents increase in time. Retention in LF1:04's water column restricts that limits of contaminant reaching the Baltic water (LF1:11) during the period of the calculation carried out here.

By 10 ka there is more activity in the second flowpath element (around 25% of the initial inventory) than anywhere else in the system. The small size of the streams in F1:01 and F1:02 means that the terrestrial soils have higher inventories that the water column. In Lake Bolundsfjärden and beyond there is more activity in the water column. These distributions reflect local FEPs in the ecosystem models and the importance of an appropriate representation of local water and solid material fluxes.

From this simple model of the landscape it is clear that timescales of the order of 10 ka are relevant for describing contaminant transport through the drainage system. This is also the timescale of significant system evolution. The release assumes that there is an input to the base of the QD from the bedrock. The consequence of this geosphere-biosphere interface interpretation is that accumulations in the QD are an important feature of the system, even for relative poorly sorbing radionuclides. Accumulation in the deeper terrestrial geology determine dynamics of doses downstream and this emphasises the importance of models of both terrestrial and aquatic sub-systems.

5 SUMMARY AND CONCLUSIONS

GEMA is a radiological assessment tool intended for use in the assessment of the consequences of radionuclide release in an evolving landscape. The essential elements of GEMA are

- a modular approach allowing elements of the surface drainage network to be combined to represent the transport and accumulation of contaminants through the landscape;
- detailed internal representation of ecosystems based on progressive developments since the early 1980s documented *inter alia* in BIOMOVS (1993), BIOMOVS II (1996) and BIOMASS (IAEA 2003). Using a compartment structure contaminant transfer processes are described in terms water and solid fluxes following the approach used in the Swiss assessment model *TAME* (Kłos *et al*. 1996); and
- a set of exposure pathways based on a traditional approach but extended to account for natural and semi-natural environments (BIOMOVS II 1996; IAEA 2003; Kłos & Albrecht 2005).

GEMA uses a traditional approach to modelling the surface environment in that a first order linear compartment model is used to represent the dynamics of environmental concentration in the physical media of the ecosystem. Conversion factors are used to calculate doses on the basis of the distribution of contaminant between the components of the GEMA model of the ecosystem. Each ecosystem model is based on the application of mass balance for water and solid material fluxes. The applications described here therefore use a representation of local hydrology to ensure the consistent treatment of contaminants in time and space.

The examples also illustrate how the ecosystems models are constructed from site specific and generic model detail. The GEMA is inherently flexible and can be applied to a wide variety of systems. This document has given a detailed outline of how site data are translated into model parameters. As such it therefore serves as a supporting document for the review of SR-Can carried out by Xu et al. (2008). The full model description also provides the QA documentation of the GEMA model.

System change is an important feature of Swedish biospheres. The step change approach is illustrated here. Currently, developments of GEMA are being finalised to allow gradual change to be modelled. As noted in the example results presented here there is a need to refine the understanding of processes leading to step changes, particularly with regard to human actions in converting wetlands to agricultural land. The example of the transport of ^{129}I along an extended drainage network gives an indication of the relevant timescales in biosphere modelling.

The numerical examples illustrate that better understanding of the processes involved in the conversion of wetlands to agricultural land is required. Applying mass conservation at the time of transition the examples show that there can be important transient doses arising as contaminant accumulations below water bodies and wetlands become incorporated in soils of agricultural land. Current site descriptive databases do not provide sufficient detail to adequately represent these FEPs.

References

Avila R. (2006) The ecosystem models used for dose assessment in SR-Can, SKB R-06-81, Svensk Kärnbränslehantering AB

Avila, R, Ekström, P-A and Kautsky, U. (2006). Development of landscape dose factors for assessments in SR-Can. SKB TR-06-15. Svensk Kärnbränslehantering AB.

BIOMOVS (1993) 'BIOMOVS Final Report'. BIOMOVS Technical Report No 15, published on behalf of the BIOMOVS Steering Committee by the Swedish Radiation Protection Institute, Stockholm, Sweden.

BIOMOVS II (1996) Biosphere modelling for dose assessments of radioactive waste repositories: final report of the Complementary Studies Working Group, ed. R. A. Kłos, BIOMOVS II Technical Report No. 12, published by the Swedish Radiation Protection Institute, Stockholm, ISBN 91-972958-1-7

Bergström, U and Barkefors, CM. (2004) Irrigation in dose assessments models, SKB Report R-04-26, SKB, Stockholm, Sweden

Bergström, U, Nordlinder, S and Aggeryd, I. (1999) Models for dose assessments Modules for various biosphere types. SKB TR-99-14. Svensk Kärnbränslehantering AB.

Global Mapper (2007) Global Mapper 7.0, Global Mapper Software LLC, PO Box 3051, Olathe, KS 66063, USA

IAEA (2003) 'Reference Biospheres' for solid radioactive waste disposal: Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, 2003, IAEA-BIOMASS-6, IAEA, Vienna, Austria.

Karlsson, S & Bergström, U. (2002) Nuclide documentation: Element specific parameter values used in the biospheric models of the safety assessments SR 97 and SAFE, SKB Report R-02-28, SKB, Stockholm, Sweden

Karlsson, S, Bergström, U. and Meili, M. (2001) Models for dose assessments Models adapted to SFR-area, Sweden. SKB TR-01-04. Svensk Kärnbränslehantering AB.

Kłos, R A, Müller-Lemans, H, Van Dorp, F, and Gribi, P. (1996) *TAME* - The Terrestrial-Aquatic Model of the Environment: Model Definition, Nagra Technical Report NTB 93-04, NAGRA, Wettingen, Switzerland; PSI Technical Report No. 96-18, Würenlingen & Villigen, Switzerland, ISSN 1019-0643.

Kłos, R A. (1999) TAME 3c User Guide. Nagra Internal Report, Nagra, Wettingen Switzerland.

Kłos, R A and Albrecht, A. (2005) The significance of agricultural vs. natural ecosystem pathways in temperate climates in assessments of long-term radiological impact, Journal of Environmental Radioactivity, 83, 137 – 169

Lindborg T. (2005) Description of surface systems: Preliminary site description, Forsmark area – version 1.2, SKB R-05-03, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Lindborg T. (2006) Description of surface systems - Preliminary site description, Laxemar area - version 1.2, SKB R-06-11, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Marklund, L. (2005) Preliminary release locations for Forsmark, private communication.

SKB, (1999) Deep repository for spent fuel SR-97 — Post closure safety. SKB TR-99-06 Main Report volume I and II, Svensk Kärnbränslehantering AB.

SKB, (2001) Lindgren, M., Pettersson, M., Karlsson, S. and Moreno, L. Project SAFE radionuclide release and dose from the SFR repository. SKB R-01-18, Svensk Kärnbränslehantering AB.

SKB, (2004) Interim main report of the safety assessment SR-Can, SKB Technical Report TR-04-11, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden

SKB, (2006a) Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. SKB TR-06-09, Svensk Kärnbränslehantering AB.

SKB, (2006b) The biosphere at Forsmark: Data, assumptions and models used in the SR-Can assessment. SKB R-06-82, Svensk Kärnbränslehantering AB.

SKB, (2006c) The biosphere at Laxemar: Data, assumptions and models used in the SR-Can assessment. SKB R-06-83, Svensk Kärnbränslehantering AB.

Wörman, A., Dverstorp, B. A., Klos, R. A. and Xu, S (2004) Role of the bio- and geosphere interface on migration pathways for 135Cs and ecological effects. Nuclear Technology. 148, 194-204.

Worman. A. (2005) Solution method for the transport equation, private communication

Xu S., Wörman A, Dverstorp B, Kłos, R A, Shaw, G and Marklund, L. (2008) SSI's independent consequence calculations in support of the regulatory review the SR-Can safety assessment, Swedish Radiation Protection Authority, Report in preparation.

Appendix A – Generic GEMA FEP matrix

The FEP matrix for GEMA is relatively straightforward (Figure A.1). The matrix assumes that water and solid fluxes might always be possible in the generic concept. Some are more likely than others and this is reflected in the shading of the matrix.

A more comprehensive listing of the FEPs active in any particular situation requires FEP analysis for the specific application. Section 3 of this report gives site specific details.

Contaminated source		release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	release, water and solid fluxes	
	uncontaminated source	water and solid fluxes	water and solid fluxes	water and solid fluxes	water and solid fluxes	water and solid fluxes	water and solid fluxes	water and solid fluxes	water and solid fluxes	water and solid fluxes	precipitation	precipitation	
water and solid fluxes, evolution		deep sediment	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	root uptake	inadvertant ingestion	inadvertant ingestion	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	top sediment	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	root uptake	inadvertant ingestion	inadvertant ingestion	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	lower water	water and solid fluxes, (diffusion), mixing	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	root uptake	drinking water	drinking water	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, (diffusion), mixing	upper water	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	root uptake	drinking water	drinking water	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	QD	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	root uptake	well water	well water	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	deep soil	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	root uptake	inadvertant ingestion	inadvertant ingestion	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	top soil	water and solid fluxes, evolution, (diffusion)	root uptake	inadvertant ingestion	inadvertant ingestion	water and solid fluxes, evolution
water and solid fluxes, evolution		water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	water and solid fluxes, evolution, (diffusion)	litter layer	root uptake	inadvertant ingestion	inadvertant ingestion	water and solid fluxes, evolution
		senescence	senescence	senescence	senescence			senescence	senescence	flora	consumption	consumption	
				waste processing	waste processing			senescence	senescence	senescence	fauna	consumption	
				waste processing	waste processing			senescence	senescence	recycling	consumption	humans	
													loss

Figure A.1. Generic features, events and processes for GEMA modules. This GEMA FEP-matrix is based on the eight GEMA compartments, uncontaminated and contaminated sources as well as generic plant and animal elements, comprising fourteen in all. Pink squares are considered not to be possible. Yellow are unlikely, green are infrequent but can arise under certain realistic circumstances. Purple are implicit in the modelling and white are common to all representations.

Appendix B – Solution method using direct matrix inversion

B.1 Mathematical basis

The compartment transport equation is

$$\frac{d\mathbf{N}}{dt} = \mathbf{\Lambda}'\mathbf{N} + \lambda_N(\mathbf{M} - \mathbf{N}) + \mathbf{S}(t), \tag{2.1}$$

where the contents are expressed in Bq.

Taking ingrowth as a "source term" to the compartments in vector **N** and including the decay term $-\lambda_N\mathbf{N}$ in the transfer matrix mean that this can be simplified to

$$\frac{d\mathbf{N}}{dt} = \mathbf{\Lambda}\mathbf{N}\ . \tag{B.1}$$

Proceeding in timesteps, the value of the solution at the k^{th} timestep is calculated as a perturbation of the solution at the previous timestep:

$$\mathbf{N}_k = \mathbf{N}_{k-1} + \frac{\partial\mathbf{N}}{\partial t}dt\ , \tag{B.2}$$

Which can be written as

$$\frac{\mathbf{N}_k - \mathbf{N}_{k-1}}{dt} = \frac{\partial\mathbf{N}}{\partial t} \equiv \mathbf{\Lambda}\langle\mathbf{N}\rangle\ , \tag{B.3}$$

where $\langle\mathbf{N}\rangle$ denotes averaging over the interval *dt*, say $\langle\mathbf{N}\rangle = \frac{(\mathbf{N}_k + \mathbf{N}_{k-1})}{2}$. The solution is then given by

$$\mathbf{N}_k = \left[\mathbf{I} - \frac{dt}{2}\mathbf{\Lambda}\right]^{-1}\left[\mathbf{I} + \frac{dt}{2}\mathbf{\Lambda}\right]\mathbf{N}_{k-1}\ . \tag{B.4}$$

Table B 1. Transfer matrix for Complementary Studies (BIOMOVS II 1996) written in terms of the GEMA compartments. In Complementary Studies there was only a single sediment compartment (taken to be TSed here) and one water compartment (LWat). Fractional transfer rates y^{-1}.

	Dsed	TSed / S	LWat / W	Uwat	Q / L	DSoil / D	TSoil / T	Litt	loss / E
Dsed	-4.42E-08	0	0	0	0	0	0	0	0
TSed / S	0	-1.26E+00	2.09E-01	0	1.04E+00	0	1.58E-02	0	0
LWat / W	0	2.85E-01	-8.01E+03	0	0	0	6.00E+01	0	7.95E+03
Uwat	0	0	0	-4.42E-08	0	0	0	0	0
Q / L	0	1.43E-03	1.04E-01	0	-6.29E-01	1.64E-02	0	0	5.08E-01
DSoil / D	0	0	0	0	1.99E+00	-2.31E+00	3.25E-01	0	0
TSoil / T	0	0	8.71E-05	0	0	6.03E+00	-6.03E+00	0	0
Litt	0	0	0	0	0	0	0	-4.42E-08	0
loss / E	0	0	0	0	0	0	0	0	-4.42E-08

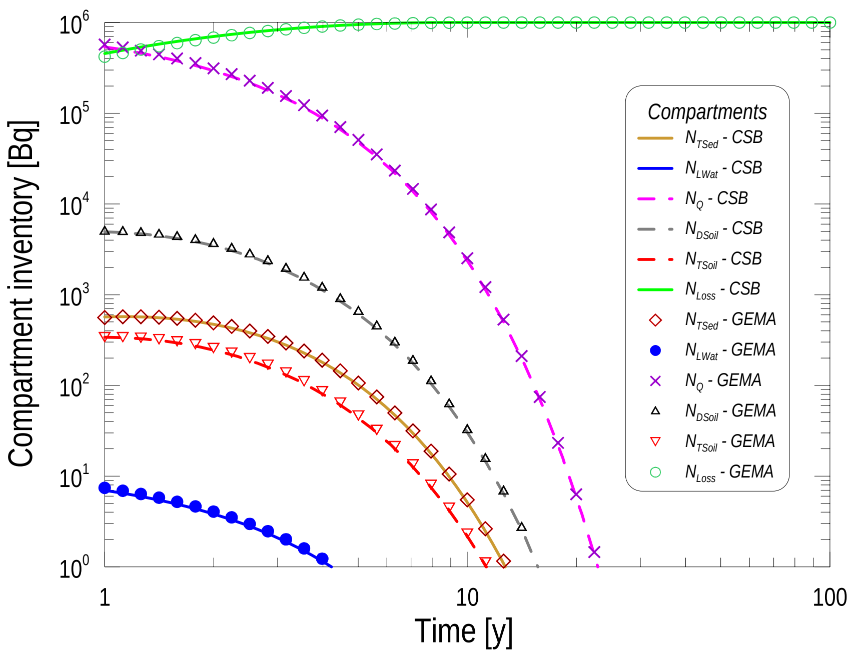


Figure B. 2. Results for an initial value problem for the Complementary Studies model. Time evolution of inventories calculated by the TAME model solver (Kłos 1999) and with the GEMA solver described above.

I is the unit matrix and the order of the matrix multiplication must be preserved. In Matlab®, this expression can be coded directly. In the GEMA codes the expression is:

```
NkpT = (I - (dt * lambda / 2)) \ (I + (dt * lambda / 2))* NkT.
```
(B.5)

The operator “\” means the inverse of the preceding matrix, i.e., **N** = **A** \ **B** is the solution to **AN** = **B**.

This method was suggested by Wörman (2005).

B.2 Numerical validation

BIOMOVS II (1996) provides the basis for the validation of the GEMA solution method. The *Complementary Studies* exercise defined a terrestrial-aquatic biosphere system. The compartment model representation, like GEMA, has a transfer matrix. Taken from the *Complementary Studies* modelling details, the matrix is shown, in GEMA format, in Table B 1.

Results are shown for an initial value problem – 1 MBq in Q at the start of the calculation. The assessment model *TAME* (Kłos *et al*. 1996) was used in the original calculations. Results from the GEMA solver are compared to those from the *TAME* solver (Kłos 1999) in Figure B. 2.

Loss from the *Complementary Studies* aquifer compartment is relatively rapid so that the initial activity is lost downstream over about 10 years. Figure B. 2 shows that there is excellent agreement between the two solution methods. This validates the use of the method outlined in Section A.1 above.

Appendix C – GEMA implementation: control and datafiles

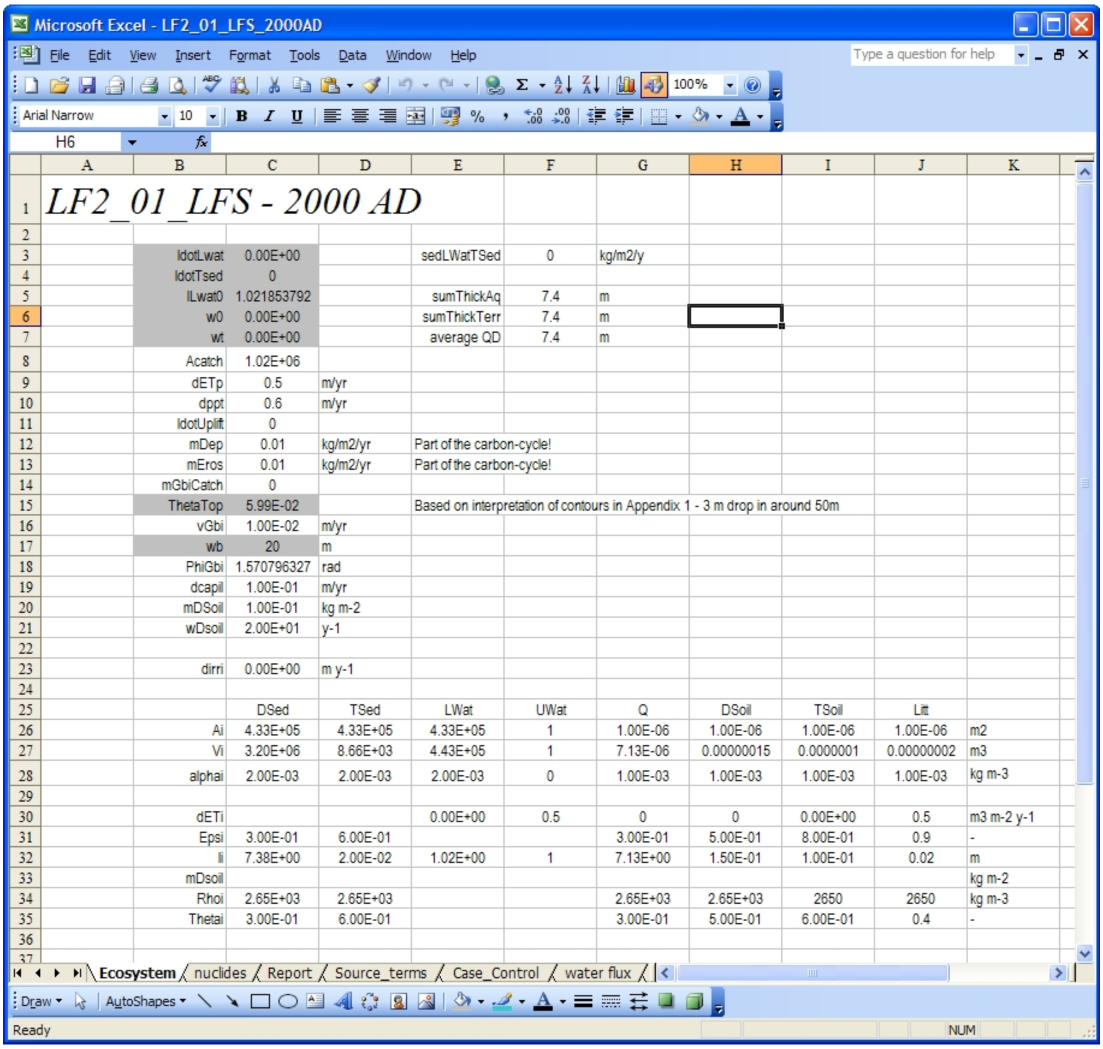
C.1 The GEMA Excel workbooks

Solution to Equation (2.1) is carried out using the GEMA Matlab® codes. All data and results are stored in a GEMA specific Excel workbooks. There are a number of specific sheets which must exist – the input data for the model, the working data for the model and the results pages for each of the radionuclides in the calculations. Before any calculation has been made the nuclide results sheets need not exist and are created via the Matlab® code. The data sheets are described below using the example of the Laxemar flowpath element LF2:01 at 2000 AD.

Required data sheets:

Ecosystem

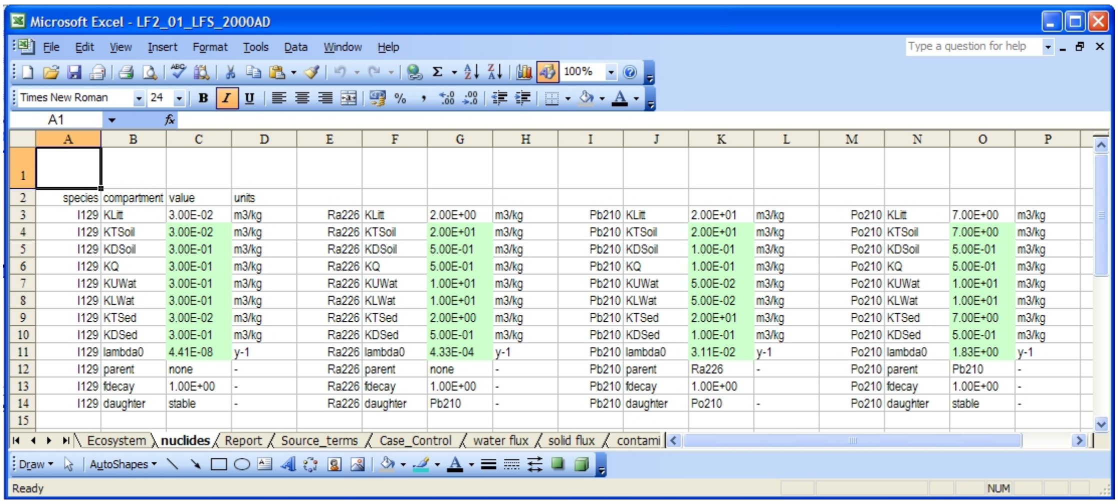
Basic data for physical characteristics of the ecosystem model. Parameters not use in the current version are shaded.



	A	B	C	D	E	F	G	H	I	J	K
1	*LF2_01_LFS - 2000 AD*										
2											
3		IdotLwat	0.00E+00		sedLWatTSed	0	kg/m2/y				
4		IdotTsed	0								
5		ILwat0	1.021853792		sumThickAq	7.4	m				
6		w0	0.00E+00		sumThickTerr	7.4	m				
7		wt	0.00E+00		average QD	7.4	m				
8		Acatch	1.02E+06								
9		dETp	0.5	m/yr							
10		dppt	0.6	m/yr							
11		IdotUplift	0								
12		mDep	0.01	kg/m2/yr	Part of the carbon-cycle!						
13		mEros	0.01	kg/m2/yr	Part of the carbon-cycle!						
14		mGbiCatch	0								
15		ThetaTop	5.99E-02		Based on interpretation of contours in Appendix 1 - 3 m drop in around 50m						
16		vGbi	1.00E-02	m/yr							
17		wb	20	m							
18		PhiGbi	1.570796327	rad							
19		dcapil	1.00E-01	m/yr							
20		mDSoil	1.00E-01	kg m-2							
21		wDsoil	2.00E+01	y-1							
22											
23		dirri	0.00E+00	m y-1							
24											
25			DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
26		Ai	4.33E+05	4.33E+05	4.33E+05	1	1.00E-06	1.00E-06	1.00E-06	1.00E-06	m2
27		Vi	3.20E+06	8.66E+03	4.43E+05	1	7.13E-06	0.00000015	0.0000001	0.00000002	m3
28		alphai	2.00E-03	2.00E-03	2.00E-03	0	1.00E-03	1.00E-03	1.00E-03	1.00E-03	kg m-3
29											
30		dETi			0.00E+00	0.5	0	0	0.00E+00	0.5	m3 m-2 y-1
31		Epsi	3.00E-01	6.00E-01			3.00E-01	5.00E-01	8.00E-01	0.9	-
32		li	7.38E+00	2.00E-02	1.02E+00	1	7.13E+00	1.50E-01	1.00E-01	0.02	m
33		mDsoil									kg m-2
34		Rhoi	2.65E+03	2.65E+03			2.65E+03	2.65E+03	2650	2650	kg m-3
35		Thetai	3.00E-01	6.00E-01			3.00E-01	5.00E-01	6.00E-01	0.4	-
36											

Nuclides

The compartment k_ds for the radionuclides are written in the format shown. The GEMA calculations is carried out for all the radionuclides listed on this sheet.

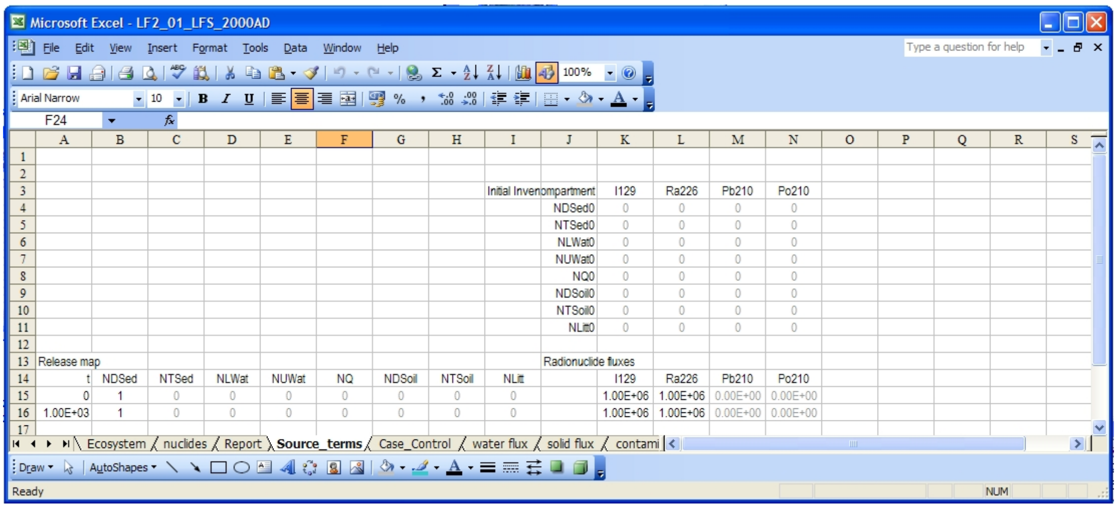


A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
species	compartment	value	units												
I129	KLitt	3.00E-02	m3/kg	Ra226	KLitt	2.00E+00	m3/kg	Pb210	KLitt	2.00E+01	m3/kg	Po210	KLitt	7.00E+00	m3/kg
I129	KTSoil	3.00E-02	m3/kg	Ra226	KTSoil	2.00E+01	m3/kg	Pb210	KTSoil	2.00E+01	m3/kg	Po210	KTSoil	7.00E+00	m3/kg
I129	KDSoil	3.00E-01	m3/kg	Ra226	KDSoil	5.00E-01	m3/kg	Pb210	KDSoil	1.00E-01	m3/kg	Po210	KDSoil	5.00E-01	m3/kg
I129	KQ	3.00E-01	m3/kg	Ra226	KQ	5.00E-01	m3/kg	Pb210	KQ	1.00E-01	m3/kg	Po210	KQ	5.00E-01	m3/kg
I129	KUWat	3.00E-01	m3/kg	Ra226	KUWat	1.00E+01	m3/kg	Pb210	KUWat	5.00E-02	m3/kg	Po210	KUWat	1.00E+01	m3/kg
I129	KLWat	3.00E-01	m3/kg	Ra226	KLWat	1.00E+01	m3/kg	Pb210	KLWat	5.00E-02	m3/kg	Po210	KLWat	1.00E+01	m3/kg
I129	KTSed	3.00E-02	m3/kg	Ra226	KTSed	2.00E+00	m3/kg	Pb210	KTSed	2.00E+01	m3/kg	Po210	KTSed	7.00E+00	m3/kg
I129	KDSed	3.00E-01	m3/kg	Ra226	KDSed	5.00E-01	m3/kg	Pb210	KDSed	1.00E-01	m3/kg	Po210	KDSed	5.00E-01	m3/kg
I129	lambda0	4.41E-08	y-1	Ra226	lambda0	4.33E-04	y-1	Pb210	lambda0	3.11E-02	y-1	Po210	lambda0	1.83E+00	y-1
I129	parent	none	-	Ra226	parent	none	-	Pb210	parent	Ra226	-	Po210	parent	Pb210	-
I129	fdecay	1.00E+00	-	Ra226	fdecay	1.00E+00	-	Pb210	fdecay	1.00E+00		Po210	fdecay	1.00E+00	-
I129	daughter	stable	-	Ra226	daughter	Pb210	-	Pb210	daughter	Po210	-	Po210	daughter	stable	-

A copy of a data for a selected nuclide can be copied to cells D17:D25. These values are used to calculate the transfer matrix on the basis of water and solid material fluxes.

Source terms

For each of the radionuclides on the *Nuclides* page the source terms and initial inventories are defined on this page.

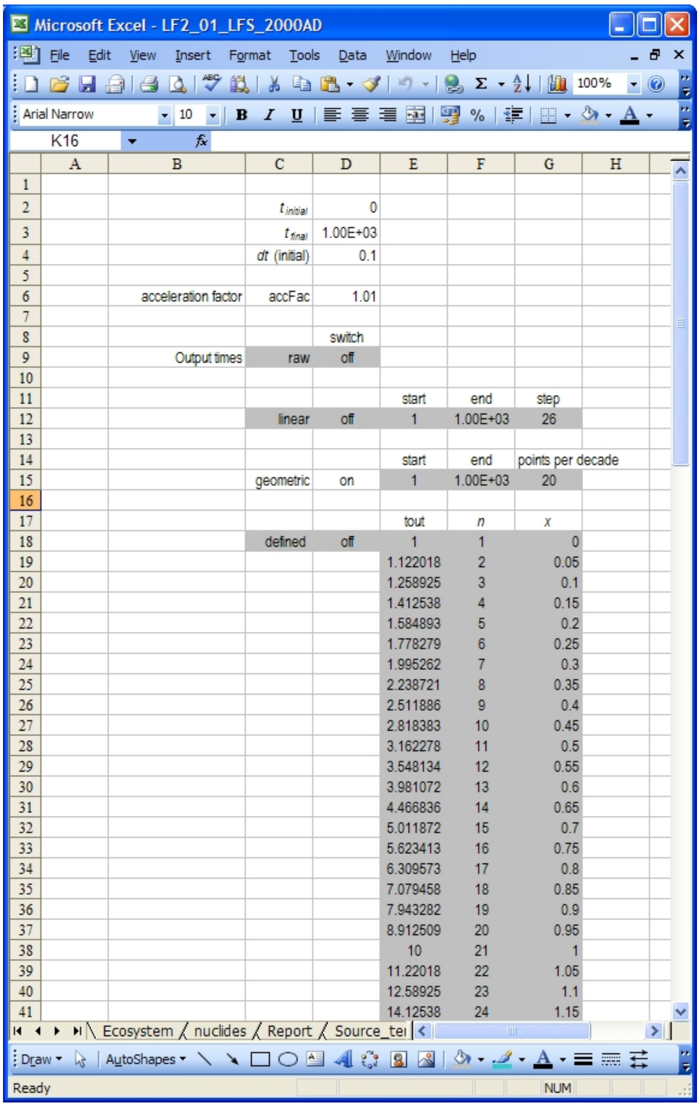


A	B	C	D	E	F	G	H	I	J	K	L	M	N
								Initial Inven	compartment	I129	Ra226	Pb210	Po210
									NDSed0	0	0	0	0
									NTSed0	0	0	0	0
									NLWat0	0	0	0	0
									NUWat0	0	0	0	0
									NQ0	0	0	0	0
									NDSoil0	0	0	0	0
									NTSoil0	0	0	0	0
									NLitt0	0	0	0	0
Release map									Radionuclide fluxes				
t	NDSed	NTSed	NLWat	NUWat	NQ	NDSoil	NTSoil	NLitt		I129	Ra226	Pb210	Po210
0	1	0	0	0	0	0	0	0		1.00E+06	1.00E+06	0.00E+00	0.00E+00
1.00E+03	1	0	0	0	0	0	0	0		1.00E+06	1.00E+06	0.00E+00	0.00E+00

Case control

This sheet controls the limits of the integration in time. The initial timestep is specified and the acceleration factor – how fast the timestep can increase to speed up the integration.

The times at which output is written to the results files are also specified from four options – raw, linear, geometric or defined. The defined option allows the used to pay special attention to edges in the results, for example around step transitions, if required.

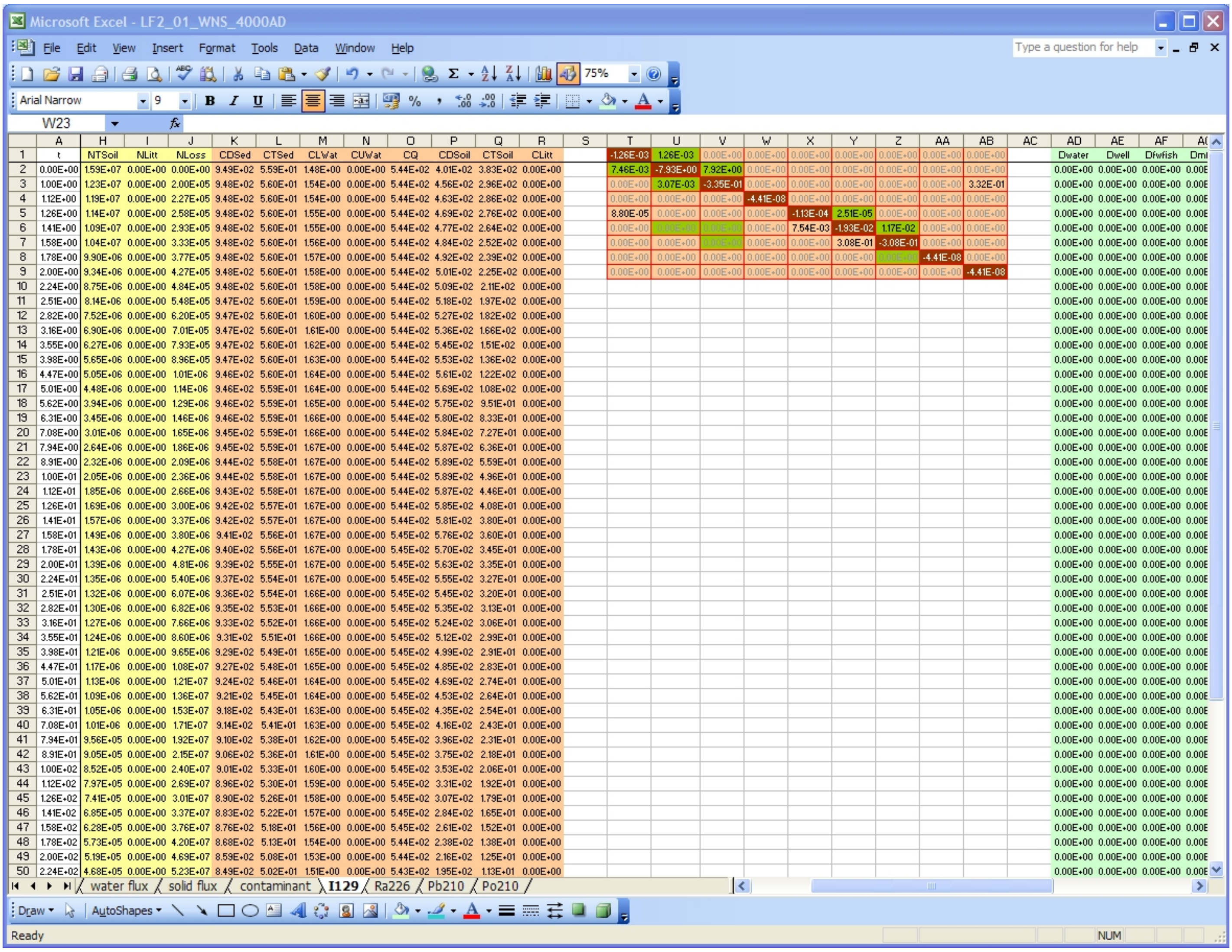


	A	B	C	D	E	F	G	H
1								
2			$t_{initial}$	0				
3			t_{final}	1.00E+03				
4			dt (initial)	0.1				
5								
6		acceleration factor	accFac	1.01				
7								
8				switch				
9		Output times	raw	off				
10								
11					start	end	step	
12			linear	off	1	1.00E+03	26	
13								
14					start	end	points per decade	
15			geometric	on	1	1.00E+03	20	
16								
17					tout	n	x	
18			defined	off	1	1	0	
19					1.122018	2	0.05	
20					1.258925	3	0.1	
21					1.412538	4	0.15	
22					1.584893	5	0.2	
23					1.778279	6	0.25	
24					1.995262	7	0.3	
25					2.238721	8	0.35	
26					2.511886	9	0.4	
27					2.818383	10	0.45	
28					3.162278	11	0.5	
29					3.548134	12	0.55	
30					3.981072	13	0.6	
31					4.466836	14	0.65	
32					5.011872	15	0.7	
33					5.623413	16	0.75	
34					6.309573	17	0.8	
35					7.079458	18	0.85	
36					7.943282	19	0.9	
37					8.912509	20	0.95	
38					10	21	1	
39					11.22018	22	1.05	
40					12.58925	23	1.1	
41					14.12538	24	1.15	

Results sheets

Nuclide

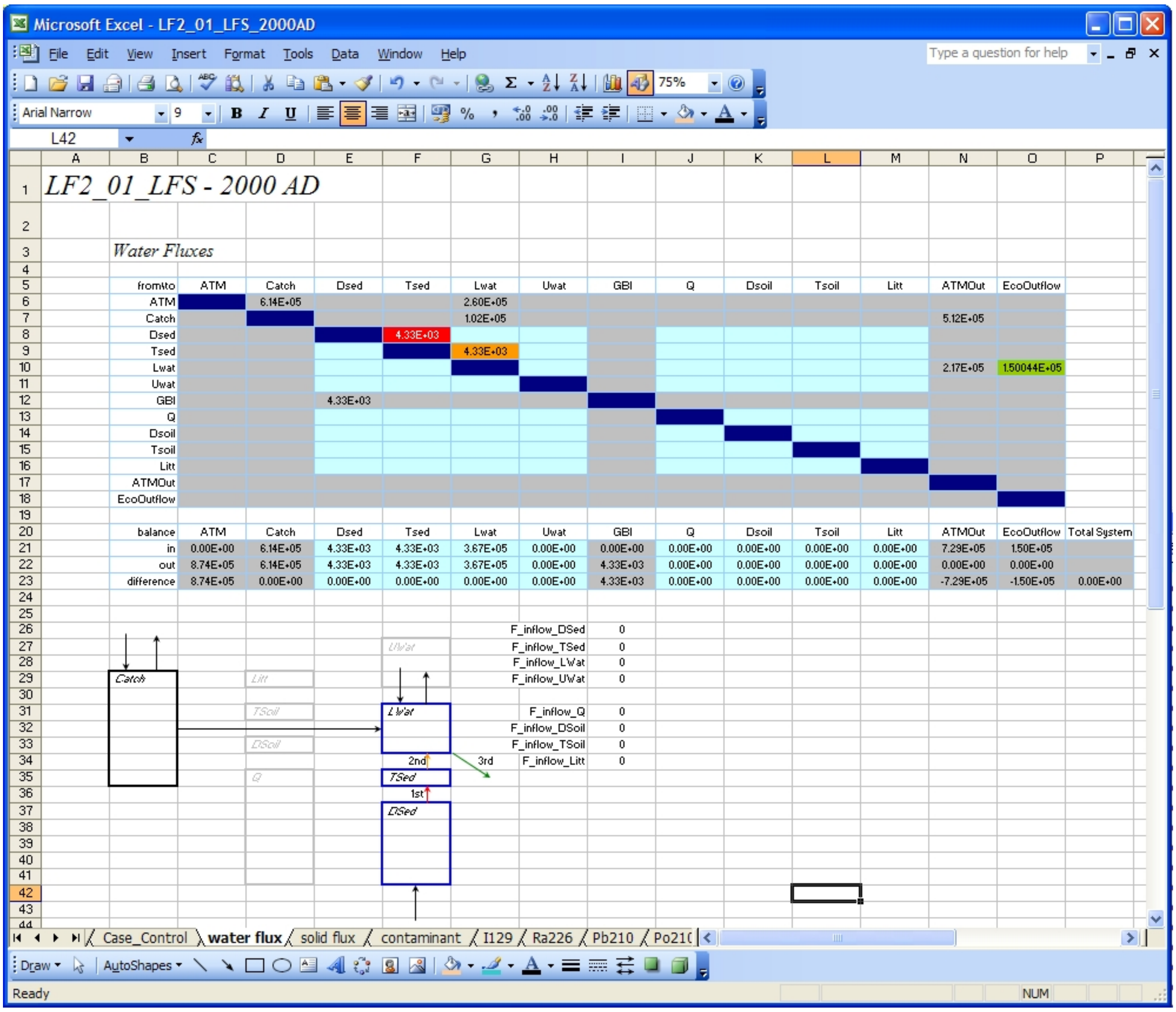
Each nuclide specified on the *nuclides* sheet has a result page created. Results stored are in columns for output time inventories and concentrations, (columns A:R) the transfer matrix (T1:AB9) calculated by the GEMA codes and the dose by pathway (columns AD:AT).



Optional sheets

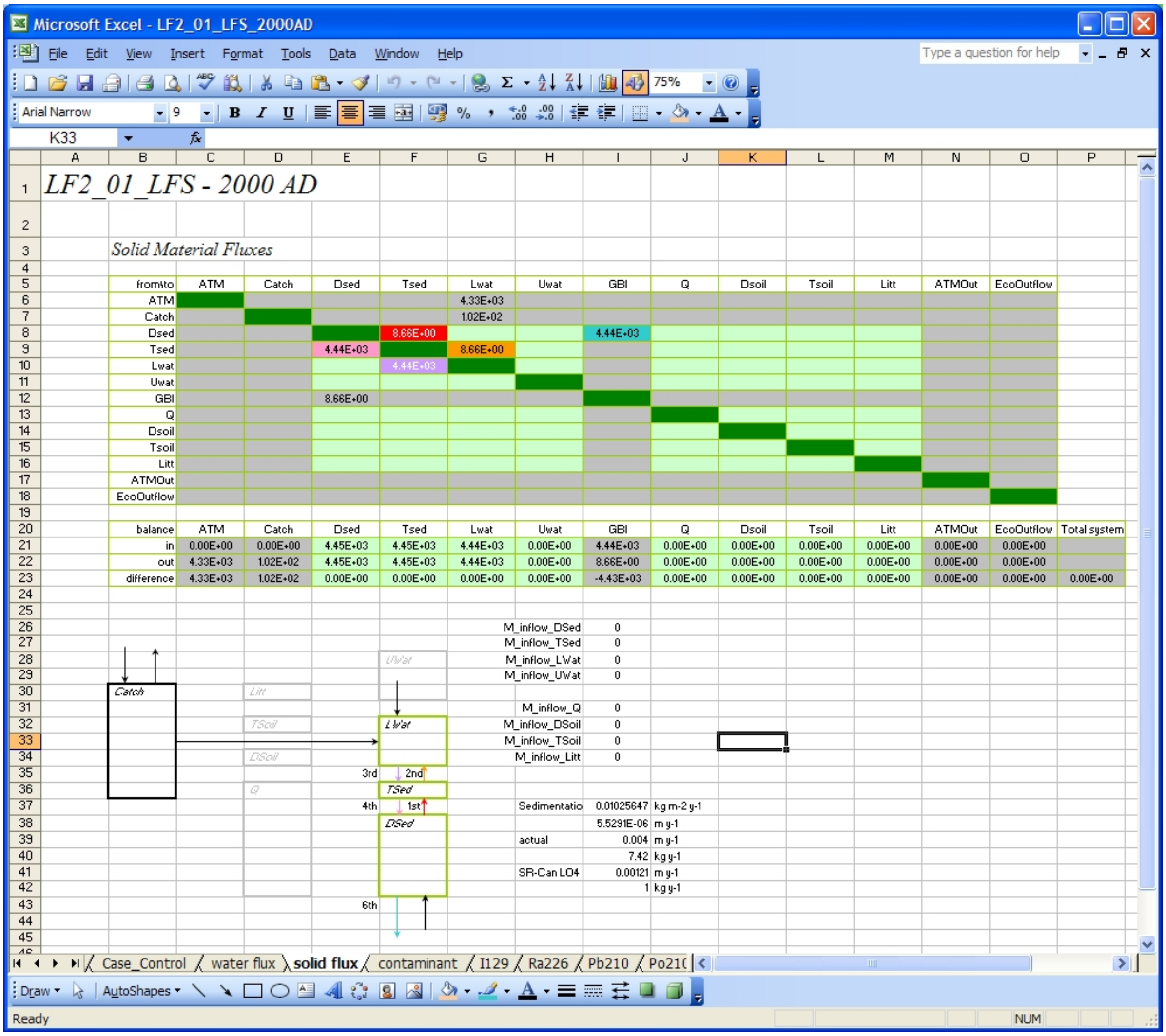
Water flux

The water flux sheet is used to construct the water flux balance for the flowpath object. As well as the internal fluxes in the system this sheet details of the inputs and outputs fluxes.



Solid flux

Equivalent to the water flux but for solid material fluxes.



LF2_01_LFS - 2000 AD

Solid Material Fluxes

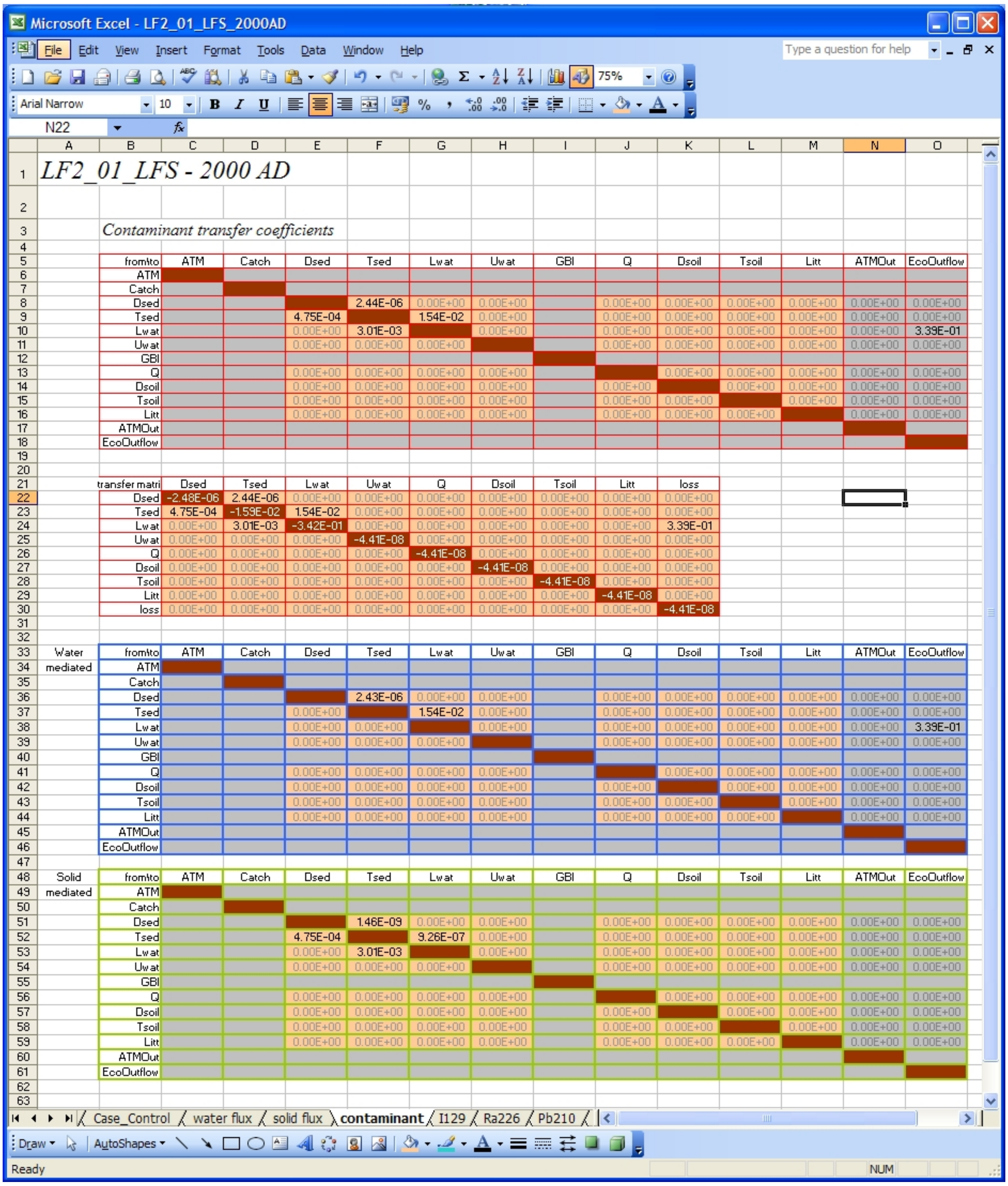
from\to	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow
ATM					4.33E+03								
Catch					1.02E+02								
Dsed				8.66E+00			4.44E+03						
Tsed			4.44E+03		8.66E+00								
Lwat				4.44E+03									
Uwat													
GBI			8.66E+00										
Q													
Dsoil													
Tsoil													
Litt													
ATMOut													
EcoOutflow													

balance	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow	Total system
in	0.00E+00	0.00E+00	4.45E+03	4.45E+03	4.44E+03	0.00E+00	4.44E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
out	4.33E+03	1.02E+02	4.45E+03	4.45E+03	4.44E+03	0.00E+00	8.66E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
difference	4.33E+03	1.02E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.43E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

M_inflow_DSed	0	
M_inflow_TSed	0	
M_inflow_LWat	0	
M_inflow_UWat	0	
M_inflow_Q	0	
M_inflow_DSoil	0	
M_inflow_TSoil	0	
M_inflow_Litt	0	
Sedimentatio	0.01025647	kg m-2 y-1
	5.5291E-06	m y-1
actual	0.004	m y-1
	7.42	kg y-1
SR-Can LO4	0.00121	m y-1
	1	kg y-1

Contaminant

Water and solid flux matrices are combined (using Equations 2.3) to give the transfer coefficients for reference.



LF2_01_LFS - 2000 AD

Contaminant transfer coefficients

from\to	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow
ATM													
Catch													
Dsed				2.44E-06	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsed			4.75E-04		1.54E-02	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Lwat			0.00E+00	3.01E-03		0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E-01
Uwat			0.00E+00	0.00E+00	0.00E+00			0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GBI													
Q			0.00E+00	0.00E+00	0.00E+00	0.00E+00			0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dsoil			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsoil			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00
Litt			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00
ATMOut													
EcoOutflow													

transfer matri	Dsed	Tsed	Lwat	Uwat	Q	Dsoil	Tsoil	Litt	loss
Dsed	-2.48E-06	2.44E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsed	4.75E-04	-1.59E-02	1.54E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Lwat	0.00E+00	3.01E-03	-3.42E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E-01
Uwat	0.00E+00	0.00E+00	0.00E+00	-4.41E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Q	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.41E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dsoil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.41E-08	0.00E+00	0.00E+00	0.00E+00
Tsoil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.41E-08	0.00E+00	0.00E+00
Litt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.41E-08	0.00E+00
loss	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.41E-08

Water mediated

from\to	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow
ATM													
Catch													
Dsed				2.43E-06	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsed			0.00E+00		1.54E-02	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Lwat			0.00E+00	0.00E+00		0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E-01
Uwat			0.00E+00	0.00E+00	0.00E+00			0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GBI													
Q			0.00E+00	0.00E+00	0.00E+00	0.00E+00			0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dsoil			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsoil			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00
Litt			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00
ATMOut													
EcoOutflow													

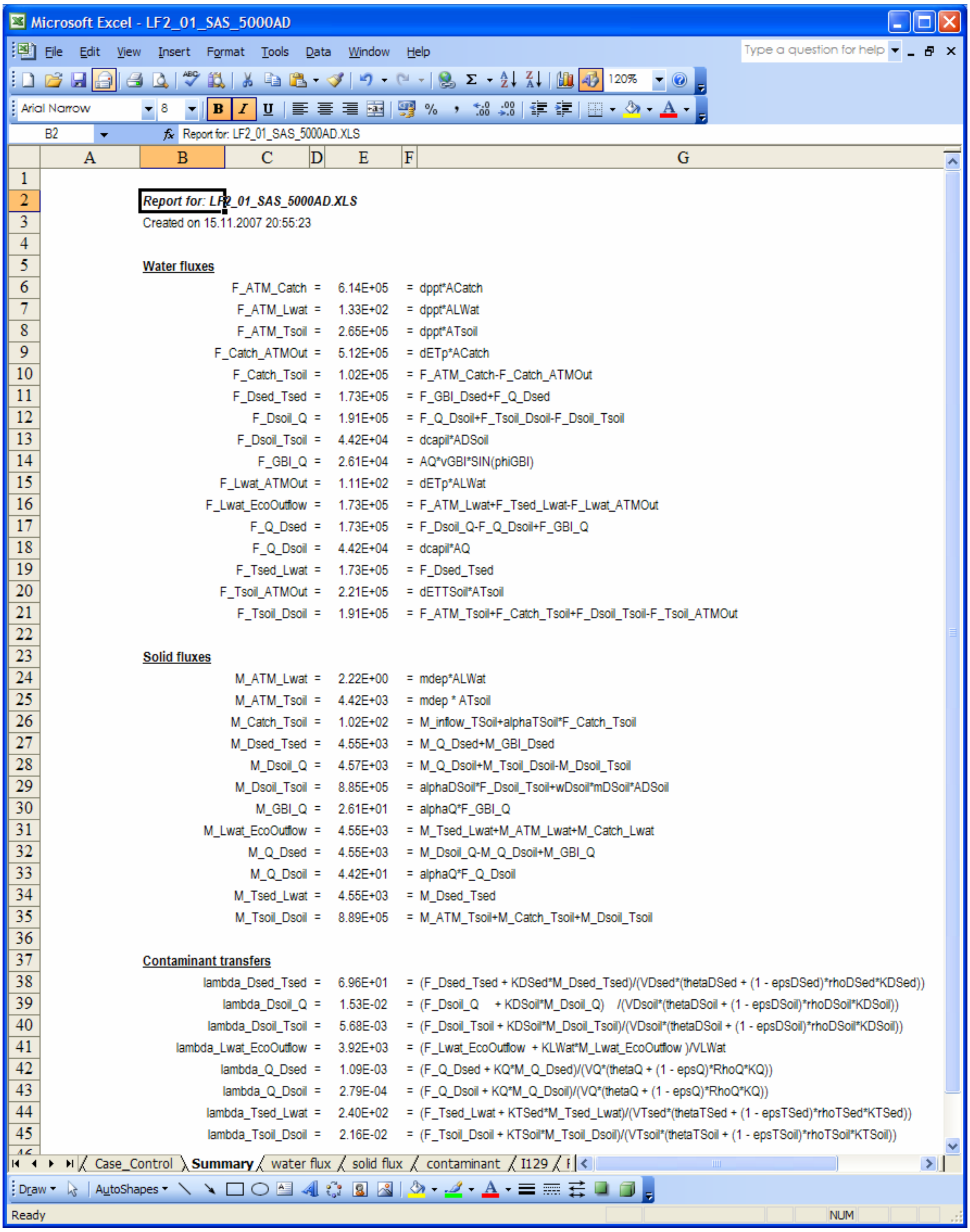
Solid mediated

from\to	ATM	Catch	Dsed	Tsed	Lwat	Uwat	GBI	Q	Dsoil	Tsoil	Litt	ATMOut	EcoOutflow
ATM													
Catch													
Dsed				1.46E-09	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsed			4.75E-04		9.26E-07	0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Lwat			0.00E+00	3.01E-03		0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Uwat			0.00E+00	0.00E+00	0.00E+00			0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GBI													
Q			0.00E+00	0.00E+00	0.00E+00	0.00E+00			0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dsoil			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tsoil			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00
Litt			0.00E+00	0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00	0.00E+00		0.00E+00	0.00E+00
ATMOut													
EcoOutflow													

Summary

The summary sheet has two functions. It provides a summary of the symbolic relationships used to define mass balance in the water and solid material flux sheets. With these it also gives the numerical values of the fluxes and shows how the transfer coefficients are calculated for **Λ**, the transfer matrix, giving the numerical values for the example nuclide selected on the Nuclide page.

Secondly, the numerical values for the water fluxes are read by the GEMA codes for use in the generation of the transfer coefficients in the GEMA run. The results for the transfer factors calculated by the GEMA codes are written to the results sheets to allow a check of the codes.



C.2 Additional output

As well as writing results to the GEMA Excel workbook a number of intermediate Matlab® mat-files are also created. Inventories, concentrations and doses are saved in each of the files:

```
lqybhpbqxf1pdw

fqfbhpbqxf1pdw

grvhbhpbqxf1pdw
```

respectively. Here, *em* is the name of the ecosystem model and *nuc* is the nuclide. Results for ^{226}Ra doses in the first part of the Laxemar LF2:01 flowpath for the 2000 AD timestep are stored as dose_LF2_01_LFS_2000AD_Ra226.mat.

These mat files can be read and manipulated by Matlab®, for example for quick plots using the GEMA Matlab commands *plot_inv*, *plot_cnc* and *plot_dose*, having first loaded the appropriate mat-file.

Similarly the transfer matrix and the water and solid fluxes are stored in

```
wuqbhpbqxf1pdw1
```

An *export* file is also created during the GEMA run:

```
wuqbhpbqxf1pdw1
```

This is the source to the downstream ecosystem model as a function of time arising from the throughflow of water and solid material. It is used with the M_exp_inp matrix of the next flowpath element found in the set_fluxes file to direct the output from upstream into the correct compartment of the next ecosystem. It comprises a set of columns for time and the flux *out* of the compartments of the preceding model.

C.3 Set_fluxes

The Set_fluxes code is used to partition the outflow from the upstream module into the current module. This takes account of the landscape transport discussed in Section 2.4. This piece of code also takes account of the step-change transitions of ecosystem inventories illustrated by the matrix in Equation (3.2).

If the upstream ecosystem has a one to one correspondence with the current module in terms of compartment characteristics the interface matrix is the identity. Similarly if the system does not change in time the identity matrix can be used although in such circumstances it would not be necessary to model the temporal transition and the current system description, as embodied in the transfer matrix $\mathbf{\Lambda}$, can be continued forward in time.

For the example of the BRH_x model discussed in Section 3.2.5 the set_fluxes coding contains the following lines:

```
Pbh{sblqs @ h|h+43,>
```

and

```
Qrog @ ilqLqy +4/ 4 . qGVhg = 4 . qOlww, >
```

```
Yrog @ ilqLqy +5/ 4 . qGVhg = 4 . qOlww, >
Drog @ ilqLqy +6/ 4 . qGVhg = 4 . qOlww, >
Orog @ ilqLqy +7/ 4 . qGVhg = 4 . qOlww, >

iwudq @ D+qOZdw, 2 Drog+qOZdw,>

vxpWhuuRog @ Orog+qT, . Orog+qGVrlo, . Orog+qWVrlo, >
sT     @ +4 0 iwudq, - Orog+qT,     2 vxpWhuuRog >
sGVrlo @ +4 0 iwudq, - Orog+qGVrlo, 2 vxpWhuuRog >
sWVrlo @ +4 0 iwudq, - Orog+qWVrlo, 2 vxpWhuuRog >

Wwudq @ ^ iwudq   3       3      3      3      3      3      3       >
          3       iwudq   3      3      3      3      3      3       >
          3       3       4      3      3      3      3      3       >
          3       3       3      4      3      3      3      3       >
          sT      sT      3      3      4      3      3      3       >
          sGVrlo  sGVrlo  3      3      3      4      3      3       >
          sWVrlo  sWVrlo  3      3      3      3      4      3       >
          3       3       3      3      3      3      3      4       ‘ >

(   Vhw UQ lqyhqwrulhv iurp suhylrxv wlph vwhs fdofxodwlrq
Qlql @ Wwudq - Qrog >
```

The first line says that the identity matrix is used to partition upstream contaminant fluxes between the current module’s compartments. The second part implements Equations (3.2) so that the initial inventories of the current module contain the correct inventory at the start of the calculations for this timestep.

C.4 GEMA implementation

From Matlab®, GEMA can be invoked for the system to be analysed. The GEMA codes handle the Excel sheets, perform the integration and calculate doses, before writing the results to the radionuclide specific pages of the ecosystem model’s Excel files. The following example (for northern Borholmsfjärden at 3000 AD) shows how the system is managed at run-time:

```
(   FOLPE hfrv|vwhp prghov Yhuvlrq 413
(       451381533:

( OI5b35 dw 6333 DG  ??????????????????????????????
fohdu
xsvwuhdpbhp @ *qrqh*>
suhylrxvbhp @ *OI5b34bEFVb5333DG*>
h{fhoberrn @ *OI5b34bOQVb6333DG*>

iox{biloh @ *vhwbiox{hvbOI5b34bOQVb6333DG*>

uhohdvhborfdwlrq @ wuxh>

grbsorw @ idovh>
grvhbsorw @ idovh>
```

```
(             34      35     36       37      38      39       3:     3;      3<     43
44     45    46     47        48     49    4:
(Grxw      @ ^ Gzdwhu Gzhoo Gizilvk Gpilvk Gizlqy Gziuxlw Gqxwv Gixqjl Gehhi
Gplon Gjdph Gyhj Gurrw Gfhuhdov Ggxvw Gh{w GVrlo'>
sdwkzd|v @ ^ 3       3      4        3       4       4        4      4       3      3
4      3     3      3         4      4     4     '>
JHPDbVUbFdqbelv

( ?????????????????????????????????????????????
```

There is no upstream ecosystem but the model uses the final inventories calculated at the end of the 20000 AD system (using `previous_em`).

The system receives an input (`release_location = true`) and the code in `set_fluxes_LF2_01_LNS_3000AD` takes account of the spatio-temporal interfaces.

The system of active dose pathways (cf. Table 3.12) is given using the `pathways` array. Finally the model is run using the command `GEMA_SR_Can_bis`.

Appendix D – Glossary of GEMA parameters

The following table provides a glossary of the GEMA dataset and provide data values and references.

ACatch	[m^2] area of local catchment
ADSed	[m^2] area of deep sediment
ADSoil	[m^2] area of deep soil
ALWat	[m^2] area of lower water
Alitt	[m^2] area of litter layer
AQ	[m^2] area of QD
ATSed	[m^2] area of top sediment
ATSoil	[m^2] area of top soil
AUWat	[m^2] area of upper water
CLWat	[Bq m^{-3}] conc. in lower water
CLitt	[Bq m^{-3}] conc. in litter layer
CQ	[Bq m^{-3}] conc. in QD
CTSoil	[Bq m^{-3}] conc. in top soil
CUWat	[Bq m^{-3}] conc. in upper water
Ccow	[Bq kg^{-1}] conc. in cow meat
Ccowintake	[Bq kg^{-1} or Bq m^{-3}] conc. n foodstuffs ingested by cattle
Cgame	[Bq kg^{-1}] conc. in cow meat
Cmilk	[Bq kg^{-1}] conc. in cow meat
Dbeef	[Sv y^{-1}] dose meat
Dcereals	[Sv y^{-1}] dose cereals
Ddust	[Sv y^{-1}] dose dust inh.
Dext	[Sv y^{-1}] dose ext dose
Dfungi	[Sv y^{-1}] dose fungi
Dfwfish	[Sv y^{-1}] dose freshwater fish
Dfwinv	[Sv y^{-1}] dose fw invertebrates
Dgame	[Sv y^{-1}] dose game
Dmfish	[Sv y^{-1}] dose marine fish
Dmilk	[Sv y^{-1}] dose milk
Dnuts	[Sv y^{-1}] dose nuts
Droot	[Sv y^{-1}] dose root veg.
Dveg	[Sv y^{-1}] dose leafy veg.
Dwater	[Sv y^{-1}] dose drink. water (surface)
Dwell	[Sv y^{-1}] dose drink. water (well)
Dwfruit	[Sv y^{-1}] dose fruit
EpsDSed	[-] Porosity deep sediment
EpsDSoil	[-] Porosity deep soil
EpsLitt	[-] Porosity litter layer
EpsQ	[-] Porosity QD
EpsTSed	[-] Porosity top sediment
EpsTSoil	[-] Porosity top soil
F_i_j	[m^3 y^{-1}] intercompartment water fluxes i, j = ATM, ATMOut, Catch, DSed, DSoil, EcoOutflow, GBI, LWat, Litt, Q, Tsed, TSoil, UWat
Hext	[Sv hour^{-1} (Bq m^{-3})$^{-1}$] external dose factor
Hing	[Sv Bq^{-1}] dose per unit intake inhalation
Hinh	[Sv Bq^{-1}] dose per unit intake ingestion
Iair	[m^3 y^{-1}] inhalation rate
Ibeef	[kg y^{-1}] intake rate of meat
Icereals	[kg y^{-1}] intake rate of cereals
Icowaqplants	[kg y^{-1}] cattle intake rate of aquatic plants
Icowpasture	[kg y^{-1}] cattle intake rate of pasture
Icowsoil	[kg y^{-1}] cattle intake rate of soils
Icowwater	[kg y^{-1}] cattle intake rate of water
Ifish	[kg y^{-1}] intake rate of fish
Ifungi	[kg y^{-1}] intake rate of mushrooms
Ifwinv	[kg y^{-1}] intake rate of invertebrates
Igame	[kg y^{-1}] intake rate of game
Igamenuts	[kg y^{-1}] game intake rate of nuts
Igamesoil	[kg y^{-1}] game intake rate of soil
Igamewater	[kg y^{-1}] game intake rate of water
Igamewfruit	[kg y^{-1}] game intake rate of fruit
Imilk	[kg y^{-1}] intake rate of milk
Inuts	[kg y^{-1}] intake rate of nuts
Iroot	[kg y^{-1}] intake rate of root veg.
Isoil	[kg y^{-1}] intake rate of soil
Iveg	[kg y^{-1}] intake rate of leafy veg.
Iwater	[kg y^{-1}] intake rate of potable water
Iwfruit	[kg y^{-1}] intake rate of wild fruit
KDSed	[m^3 kg^{-1}] deep sediment k_d
KDSoil	[m^3 kg^{-1}] deep soil k_d
KLWat	[m^3 kg^{-1}] k_d in lower water
KLitt	[m^3 kg^{-1}] litter layer k_d
KQ	[m^3 kg^{-1}] QD k_d
KTSed	[m^3 kg^{-1}] top sediment k_d
KTSoil	[m^3 kg^{-1}] top soil k_d
KUWat	[m^3 kg^{-1}] k_d in upper water
Kaqplants	[-] concentration factor in aquatic plants
Kbeef	[day kg^{-1}] accumulation factor meat
Kcereals	[-] concentration factor in cereals
Kfungi	[-] concentration factor in fungi
Kfwfish	[day kg^{-1}] accumulation factor fw fish
Kfwinv	[day kg^{-1}] accumulation factor invertebrates
Kmfish	[day kg^{-1}] accumulation factor marine fish
Kmilk	[day kg^{-1}] accumulation factor milk
Knuts	[-] concentration factor in nuts
Kpasture	[-] concentration factor in pasture
Kroot	[-] concentration factor in root veg.
Kveg	[-] concentration factor in leafy veg.
Kwfruit	[-] concentration factor in wild fruit
LDSed	[m] thickness deep sediment
LDSoil	[m] thickness deep soil

LLWat	[m] thickness deep lower water
LLitt	[m] thickness deep litter layer
LQ	[m] thickness deep QD
LTSed	[m] thickness deep top sediment
LTSoil	[m] thickness top soil
LUWat	[m] thickness upper water
M_i_j	[kg y^{-1}] intercomp. solid material fluxes i, j = ATM, ATMOut, Catch, DSed, DSoil, EcoOutflow, GBI, LWat, Litt, Q, Tsed, TSoil, UWat
Nexport	[Bq y^{-1}] exported "source term"
OccF	[hours y^{-1}] occupancy factor
RhoDSed	[kg m^{-3}] density deep sediment
RhoDSoil	[kg m^{-3}] density deep soil
RhoLWat	[kg m^{-3}] density lower water
RhoLitt	[kg m^{-3}] density litter layer
RhoQ	[kg m^{-3}] density QD
RhoTSed	[kg m^{-3}] density top sediment
RhoTSoil	[kg m^{-3}] density top soil
RhoUWat	[kg m^{-3}] density upper water
RhoWater	[kg m^{-3}] density water
Tcereals	[-] translocation factor cereals
ThetaDSed	[-] volumetric moisture content deep sed.
ThetaDSoil	[-] volumetric moisture content deep soil
ThetaLitt	[-] volumetric moisture content litter layer
ThetaQ	[-] volumetric moisture content QD
ThetaTSed	[-] volumetric moisture content top sed.
ThetaTSoil	[-] volumetric moisture content top soil
Troot	[-] translocation factor root veg.
VDSed	[m^3] volume deep sediment
VDSoil	[m^3] volume deep soil
VLWat	[m^3] volume lower water
VLitt	[m^3] volume litter layer
VQ	[m^3] volume QD
VTSed	[m^3] volume top sediment
VTSoil	[m^3] volume top soil
VUWat	[m^3] volume upper water
accFac	[-] integration acceleration factor
alphaAir	[kg m^{-3}] airborne dust load
alphaDSed	[kg m^{-3}] susp. Solid load deep sediment
alphaDSoil	[kg m^{-3}] susp. Solid load deep soil
alphaLWat	[kg m^{-3}] susp. Solid load lower water
alphaLitt	[kg m^{-3}] susp. Solid load litter layer
alphaQ	[kg m^{-3}] susp. Solid load QD
alphaTSed	[kg m^{-3}] susp. Solid load top sediment
alphaTSoil	[kg m^{-3}] susp. Solid load top soil
alphaUWat	[kg m^{-3}] susp. Solid load upper water
dET	[m^3 m^{-2} y^{-1}] evapotranspiration rate
dcapil	[m y^{-1}] capillary rise
dirri	[m^3 m^{-2} y^{-1}] irrigation rate
dppt	[m^3 m^{-2} y^{-1}] annual precipitation
sumThickAq	[m] thickness to aquatic compartments
sumThickTerr	[m] thickness terrestrial compartments
t	time
taudpy	[day y^{-1}] days per year
taushore	[day y^{-1}] time spent on shore
vGBI	[m^3 y^{-1}] groundwater vel. into biosphere
wDSoil	[kg m^{-2}] bioturbation activity

Appendix E – GEMA Data description for Models featured in this report

Section 3 illustrates the way in which the GEMA models is populated with. This appendix lists all the data for the GEMA modules for northern Borholmsfjärden (LF2:01) and Borholmsfjärden *extreme* (BRH_x). This is the complete dataset for the transfer matrix for northern Borholmsfjärden. The dataset used for the Bolundsfjärden drainage system is also given.

Additional GEMA data used in the review of SR-Can (Xu *et al*. 2008) can be obtained on request, from the author.

Northern Borholmsfjärden: LF2:01

There are five system states used to describe the evolution of northern Borholmsfjärden:

- 2000 – 3000 AD - LF2_01_BCS_2000AD.xls
- 3000 – 4000 AD - LF2_01_LNS_3000AD.xls
- 4000 – 5000 AD - LF2_01_SAS_5000AD.xls
- 5000 – 10 000 AD - LF2_01_WNS_4000AD.xls

LF2:01	northern Borholmsfjärden					
Tot. area catchment	1466594	m^2				
Total QD	7.4	m	Water area	Water depth	stream length	soil area
year AD	Δ sea level m	Type	m^2	m	m	m^2
2000	0	BCS	442534.4	1.0		27700
3000	-1	LNS	195386	0.5		274848.4
4000	-2	WNS	28105	0.3		442129.4
5000	-3	SAS	222	0.1	1110	470234.4
10000	-8	SAS	222	0.1	1110	470234.4

Borholmsfjärden *extreme*: BRH_x

There are four system states used to describe the evolution of northern Borholmsfjärden:

- 2000 – 3000 AD – BRH_x_2000AD.xls
- 3000 – 4000 AD – BRH_x_3000AD.xls
- 4000 – 10000 AD – BRH_x_4000AD.xls

BRH_x	Borholmsfjärden *extreme*					
Tot. area catchment	36341	m^2				
Total QD	7.4	m	Water area	Water depth	stream length	soil area
year AD	Δ sea level m	Type	m^2	m	m	m^2
2000	0	LNS	16731	0.27		0
3000	-1	WNS	3099	0.2		13632
4000	-2	SAS	115	0.1		16616
10000	-8	SAS	115	0.1	57.5	16616

The following numerical values are the basis for the calculations. Data from the GEMA ecosystem sheet are given. These data are used to derive the water and solid material fluxes. Data for these are taken from the GEMA Summary sheet. The k_d values for each of the radionuclides are taken from Table 3.7. These allow the transfer matrix Λ to be calculated for each radionuclide in each system state. The example results for the transfer coefficients are for ^{129}I. The GEMA glossary in Appendix D gives the meanings of the parameter names.

Northern Borholmsfjärden: LF2:01

LF2_01_BCS - 2000 AD

Acatch	1024059.6		vGbi	0.059	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	7.4	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	442534.4	442534.4	442534.4	1	0.000001	0.000001	0.000001	0.000001	m2
Vi	3230501.12	44253.44	452181.622	1	7.15E-06	0.00000015	0.0000001	1E-18	m3
alphai	0.002	0.002	0.002	0	0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6	0	0	0.3	0.5	0.8	0.9	-
li	7.3	0.1	1.02179994	1	7.15	0.15	0.1	1E-12	m
Rhoi	2650	2650	0	0	2650	2650	2650	2650	kg m-3

Fluxes 2000 AD – 3000 AD

Water fluxes				
F_ATM_Catch	=	6.14E+05	=	dppt*ACatch
F_ATM_Lwat	=	2.66E+05	=	dppt*ALWat
F_Catch_Lwat	=	1.02E+05	=	F_inflow_LWat+F_ATM_Catch-F_Catch_ATMOut
F_Catch_ATMOut	=	5.12E+05	=	dETp*ACatch
F_Dsed_Tsed	=	2.61E+04	=	F_GBI_Dsed
F_Tsed_Lwat	=	2.61E+04	=	F_Dsed_Tsed
F_Lwat_ATMOut	=	2.21E+05	=	dETp*ALWat
F_Lwat_EcoOutflow	=	1.73E+05	=	F_ATM_Lwat-F_Lwat_ATMOut+F_Catch_Lwat+F_Tsed_Lwat
F_GBI_Dsed	=	2.61E+04	=	ADSed*vGBI*SIN(phiGBI)
Solid fluxes				
M_ATM_Lwat	=	4.43E+03	=	mdep*ALWat
M_Catch_Lwat	=	1.02E+02	=	M_inflow_LWat+alphaQ*F_Catch_Lwat
M_Dsed_Tsed	=	5.22E+01	=	M_GBI_Dsed
M_Dsed_GBI	=	4.58E+03	=	M_Tsed_Dsed
M_Tsed_Dsed	=	4.58E+03	=	M_Lwat_Tsed
M_Tsed_Lwat	=	5.22E+01	=	M_Dsed_Tsed
M_Lwat_Tsed	=	4.58E+03	=	M_Tsed_Lwat+M_Catch_Lwat+M_ATM_Lwat
M_GBI_Dsed	=	5.22E+01	=	alphaDSed*F_GBI_Dsed
Contaminant transfers: Iodine-129				
lambda_Dsed_Tsed	=	1.44E-04	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Dsed	=	9.58E-05	=	(F_Tsed_Dsed + KTSed*M_Tsed_Dsed)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Tsed_Lwat	=	1.82E-02	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_Tsed	=	3.04E-03	=	(F_Lwat_Tsed + KLWat*M_Lwat_Tsed)/VLWat
lambda_Lwat_EcoOutflow	=	3.82E-01	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat

LF2_01_LNS - 3000 AD

Acatch	1024059.6		vGbi	0.059	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	7.4	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	297611.1	297611.1	297611.1	1	144923.3	144923.3	144923.3	144923.3	m2
Vi	2172561.03	29761.11	155708.825	1	1036201.6	21738.495	14492.33	1.4492E-07	m3
alphai	0.002	0.002	0.002	0	0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6	0	0	0.3	0.3	0.3	0.9	-
li	7.3	0.1	0.52319562	1	7.15	0.15	0.1	1E-12	m
Rhoi	2650	2650	0	0	2650	2650	2650	2650	kg m-3

Fluxes 3000 AD – 4000 AD

Water fluxes

F_ATM_Catch	=	6.14E+05	=	dppt*ACatch
F_ATM_Lwat	=	1.79E+05	=	dppt*ALWat
F_ATM_Tsoil	=	8.70E+04	=	dppt*ATsoil
F_Catch_ATMOut	=	5.12E+05	=	dETp*ACatch
F_Catch_Tsoil	=	1.02E+05	=	F_ATM_Catch-F_Catch_ATMOut
F_Dsed_Tsed	=	1.43E+05	=	F_GBI_Dsed+F_Q_Dsed
F_Dsoil_Q	=	1.31E+05	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	1.45E+04	=	dcapil*ADSoil
F_GBI_Dsed	=	1.76E+04	=	ADSed*vGBI*SIN(phiGBI)
F_GBI_Q	=	8.55E+03	=	AQ*vGBI*SIN(phiGBI)
F_Lwat_ATMOut	=	1.49E+05	=	dETp*ALWat
F_Lwat_EcoOutflow	=	1.73E+05	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_Q_Dsed	=	1.25E+05	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q
F_Q_Dsoil	=	1.45E+04	=	dcapil*AQ
F_Tsed_Lwat	=	1.43E+05	=	F_Dsed_Tsed
F_Tsoil_ATMOut	=	7.25E+04	=	dETTSoil*ATsoil
F_Tsoil_Dsoil	=	1.31E+05	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut

Solid fluxes

M_ATM_Lwat	=	2.98E+03	=	mdep*ALWat
M_ATM_Tsoil	=	1.45E+03	=	mdep * ATsoil
M_Catch_Tsoil	=	1.02E+02	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil
M_Dsed_GBI	=	4.57E+03	=	M_Tsed_Dsed+M_GBI_Dsed+M_Q_Dsed-M_Dsed_Tsed
M_Dsed_Tsed	=	1.60E+03	=	M_Q_Dsed+M_GBI_Dsed
M_Dsoil_Q	=	1.57E+03	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	2.90E+05	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_GBI_Dsed	=	3.51E+01	=	alphaDSed*F_GBI_Dsed
M_GBI_Q	=	8.55E+00	=	alphaQ*F_GBI_Q
M_Lwat_Tsed	=	4.57E+03	=	M_ATM_Lwat+M_Tsed_Lwat
M_Q_Dsed	=	1.56E+03	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q
M_Q_Dsoil	=	1.45E+01	=	alphaQ*F_Q_Dsoil
M_Tsed_Dsed	=	4.57E+03	=	M_Dsed_Tsed+M_Lwat_Tsed-M_Tsed_Lwat
M_Tsed_Lwat	=	1.60E+03	=	M_Dsed_Tsed
M_Tsoil_Dsoil	=	2.91E+05	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil

Contaminant transfers – iodine-129

lambda_Dsed_Tsed	=	1.11E-03	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Dsed	=	1.42E-04	=	(F_Tsed_Dsed + KTSed*M_Tsed_Dsed)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Tsed_Lwat	=	1.39E-01	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_Tsed	=	8.79E-03	=	(F_Lwat_Tsed + KLWat*M_Lwat_Tsed)/VLWat
lambda_Lwat_EcoOutflow	=	1.05E+00	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat
lambda_Q_Dsed	=	2.02E-03	=	(F_Q_Dsed + KQ*M_Q_Dsed)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Q_Dsoil	=	2.50E-04	=	(F_Q_Dsoil + KQ*M_Q_Dsoil)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Dsoil_Q	=	1.08E-01	=	(F_Dsoil_Q + KDSoil*M_Dsoil_Q) /(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsoil	=	1.91E-02	=	(F_Dsoil_Tsoil + KDSoil*M_Dsoil_Tsoil)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Tsoil_Dsoil	=	2.71E-02	=	(F_Tsoil_Dsoil + KTSoil*M_Tsoil_Dsoil)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))

LF2_01_WNS - 4000 AD

Acatch	1024059.6		vGbi	0.059	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	7.4	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	28105	28105	28105	1	414429.4	414429.4	414429.4	414429.4	m2
Vi	205166.5	2810.5	7479.85	1	2963170.21	62164.41	41442.94	4.1443E-07	m3
alphai	0.002	0.002	0.002	0	0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6	0	0	0.3	0.3	0.3	0.9	-
li	7.3	0.1	0.26613948	1	7.15	0.15	0.1	1E-12	m
Rhoi	2650	2650	0	0	2650	2650	2650	2650	kg m-3

Fluxes 4000 AD – 5000 AD

Water fluxes

F_ATM_Catch	=	6.14E+05	=	dppt*ACatch
F_ATM_Lwat	=	1.69E+04	=	dppt*ALWat
F_ATM_Tsoil	=	2.49E+05	=	dppt*ATsoil
F_Catch_Tsoil	=	1.02E+05	=	F_ATM_Catch-F_Catch_ATMOut
F_Catch_ATMOut	=	5.12E+05	=	dETp*ACatch
F_Dsed_Tsed	=	1.70E+05	=	F_GBI_Dsed+F_Q_Dsed
F_Tsed_Lwat	=	1.70E+05	=	F_Dsed_Tsed
F_Lwat_ATMOut	=	1.41E+04	=	dETp*ALWat
F_Lwat_EcoOutflow	=	1.73E+05	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_GBI_Dsed	=	1.66E+03	=	ADSed*vGBI*SIN(phiGBI)
F_GBI_Q	=	2.45E+04	=	AQ*vGBI*SIN(phiGBI)
F_Q_Dsed	=	1.68E+05	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q
F_Q_Dsoil	=	4.14E+04	=	dcapil*AQ
F_Dsoil_Q	=	1.85E+05	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	4.14E+04	=	dcapil*ADSoil
F_Tsoil_Dsoil	=	1.85E+05	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut
F_Tsoil_ATMOut	=	2.07E+05	=	dETTSoil*ATsoil

Solid fluxes

M_ATM_Lwat	=	2.81E+02	=	mdep*ALWat
M_ATM_Tsoil	=	4.14E+03	=	mdep * ATsoil
M_Catch_Tsoil	=	1.02E+02	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil
M_Dsed_Tsed	=	4.27E+03	=	M_Q_Dsed+M_GBI_Dsed
M_Dsed_GBI	=	4.56E+03	=	M_Tsed_Dsed+M_GBI_Dsed+M_Q_Dsed-M_Dsed_Tsed
M_Tsed_Dsed	=	4.56E+03	=	M_Dsed_Tsed+M_Lwat_Tsed-M_Tsed_Lwat
M_Tsed_Lwat	=	4.27E+03	=	M_Dsed_Tsed
M_Lwat_Tsed	=	4.56E+03	=	M_ATM_Lwat+M_Tsed_Lwat
M_GBI_Dsed	=	3.32E+00	=	alphaDSed*F_GBI_Dsed
M_GBI_Q	=	2.45E+01	=	alphaQ*F_GBI_Q
M_Q_Dsed	=	4.27E+03	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q
M_Q_Dsoil	=	4.14E+01	=	alphaQ*F_Q_Dsoil
M_Dsoil_Q	=	4.29E+03	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	8.29E+05	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_Tsoil_Dsoil	=	8.33E+05	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil

Contaminant transfers: Iodine-129

lambda_Dsed_Tsed	=	1.28E-03	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Dsed	=	1.49E-03	=	(F_Tsed_Dsed + KTSed*M_Tsed_Dsed)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Tsed_Lwat	=	1.60E+00	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_Tsed	=	1.82E-01	=	(F_Lwat_Tsed + KLWat*M_Lwat_Tsed)/VLWat
lambda_Lwat_EcoOutflow	=	1.98E+01	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat
lambda_Q_Dsed	=	8.80E-05	=	(F_Q_Dsed + KQ*M_Q_Dsed)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Q_Dsoil	=	2.51E-05	=	(F_Q_Dsoil + KQ*M_Q_Dsoil)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Dsoil_Q	=	5.39E-03	=	(F_Dsoil_Q + KDSoil*M_Dsoil_Q) /(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsoil	=	8.38E-03	=	(F_Dsoil_Tsoil + KDSoil*M_Dsoil_Tsoil)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Tsoil_Dsoil	=	9.08E-02	=	(F_Tsoil_Dsoil + KTSoil*M_Tsoil_Dsoil)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))

LF2_01_SAS - 5000 AD

Acatch	1024059.6		vGbi	0.059	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	0.3	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	222	222	222	1	442312.4	442312.4	442312.4	442312.4	m2
Vi	44.4	22.2	44.4	1E-33	2830799.36	309618.68	132693.72	4.4231E-28	m3
alphai	0.002	0.002	0.002	0	0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6	0	0	0.3	0.5	0.8	0.9	-
li	0.2	0.1	0.2	1E-33	6.4	0.7	0.3	1E-33	m
Rhoi	2650	2650	0	0	2650	2650	2650	2650	kg m-3

Fluxes 5000 AD – 10000 AD

Water fluxes

F_ATM_Catch	=	6.14E+05	=	dppt*ACatch
F_ATM_Lwat	=	1.33E+02	=	dppt*ALWat
F_ATM_Tsoil	=	2.65E+05	=	dppt*ATsoil
F_Catch_ATMOut	=	5.12E+05	=	dETp*ACatch
F_Catch_Tsoil	=	1.02E+05	=	F_ATM_Catch-F_Catch_ATMOut
F_Dsed_Tsed	=	1.73E+05	=	F_GBI_Dsed+F_Q_Dsed
F_Dsoil_Q	=	1.91E+05	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	4.42E+04	=	dcapil*ADSoil
F_GBI_Q	=	2.61E+04	=	AQ*vGBI*SIN(phiGBI)
F_Lwat_ATMOut	=	1.11E+02	=	dETp*ALWat
F_Lwat_EcoOutflow	=	1.73E+05	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_Q_Dsed	=	1.73E+05	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q
F_Q_Dsoil	=	4.42E+04	=	dcapil*AQ
F_Tsed_Lwat	=	1.73E+05	=	F_Dsed_Tsed
F_Tsoil_ATMOut	=	2.21E+05	=	dETTSoil*ATsoil
F_Tsoil_Dsoil	=	1.91E+05	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut

Solid fluxes

M_ATM_Lwat	=	2.22E+00	=	mdep*ALWat
M_ATM_Tsoil	=	4.42E+03	=	mdep * ATsoil
M_Catch_Tsoil	=	1.02E+02	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil
M_Dsed_Tsed	=	4.55E+03	=	M_Q_Dsed+M_GBI_Dsed
M_Dsoil_Q	=	4.57E+03	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	8.85E+05	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_GBI_Q	=	2.61E+01	=	alphaQ*F_GBI_Q
M_Lwat_EcoOutflow	=	4.55E+03	=	M_Tsed_Lwat+M_ATM_Lwat+M_Catch_Lwat
M_Q_Dsed	=	4.55E+03	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q
M_Q_Dsoil	=	4.42E+01	=	alphaQ*F_Q_Dsoil
M_Tsed_Lwat	=	4.55E+03	=	M_Dsed_Tsed
M_Tsoil_Dsoil	=	8.89E+05	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil

Contaminant transfers: iodine-129

lambda_Dsed_Tsed	=	6.96E+01	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Lwat	=	2.40E+02	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_EcoOutflow	=	3.92E+03	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat
lambda_Q_Dsed	=	1.09E-03	=	(F_Q_Dsed + KQ*M_Q_Dsed)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Q_Dsoil	=	2.79E-04	=	(F_Q_Dsoil + KQ*M_Q_Dsoil)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Dsoil_Q	=	1.53E-02	=	(F_Dsoil_Q + KDSoil*M_Dsoil_Q) /(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsoil	=	5.68E-03	=	(F_Dsoil_Tsoil + KDSoil*M_Dsoil_Tsoil)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Tsoil_Dsoil	=	2.16E-02	=	(F_Tsoil_Dsoil + KTSoil*M_Tsoil_Dsoil)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))

Borholmsfjärden *extreme*: BRH_x

BRH_x_LNS_2000 AD

Acatch	3.63E+04		vGbi	5.90E-02	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	1.00E-01	m/yr	sumThickAq	7.4	m
mDep	0.01	kg/m2/yr	mDSoil	1.00E-01	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	2.00E+01	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0.00E+00	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	1.67E+04	1.67E+04	1.67E+04	1	1.00E-06	1.00E-06	1.00E-06	1.00E-06	m2
Vi	1.22E+05	1.67E+03	4.45E+03	1	7.15E-06	0.00000015	0.0000001	1E-18	m3
alphai	2.00E-03	2.00E-03	2.00E-03	0	1.00E-03	1.00E-03	1.00E-03	1.00E-03	kg m-3
Epsi	3.00E-01	6.00E-01	0	0	3.00E-01	5.00E-01	8.00E-01	0.9	-
li	7.30E+00	1.00E-01	2.66E-01	1	7.15E+00	1.50E-01	1.00E-01	1.00E-12	m
Rhoi	2.65E+03	2.65E+03	0	0	2.65E+03	2.65E+03	2650	2650	kg m-3

Water fluxes

F_ATM_Catch	=	2.18E+04	=	dppt*ACatch
F_ATM_Lwat	=	1.00E+04	=	dppt*ALWat
F_Catch_Lwat	=	3.63E+03	=	F_inflow_LWat+F_ATM_Catch-F_Catch_ATMOut
F_Catch_ATMOut	=	1.82E+04	=	dETp*ACatch
F_Dsed_Tsed	=	9.87E+02	=	F_GBI_Dsed
F_Tsed_Lwat	=	9.87E+02	=	F_Dsed_Tsed
F_Lwat_ATMOut	=	8.37E+03	=	dETp*ALWat
F_Lwat_EcoOutflow	=	6.29E+03	=	F_ATM_Lwat-F_Lwat_ATMOut+F_Catch_Lwat+F_Tsed_Lwat
F_GBI_Dsed	=	9.87E+02	=	ADSed*vGBI*SIN(phiGBI)

Solid fluxes

M_ATM_Lwat	=	1.67E+02	=	mdep*ALWat
M_Catch_Lwat	=	3.63E+00	=	M_inflow_LWat+alphaQ*F_Catch_Lwat
M_Dsed_Tsed	=	1.97E+00	=	M_GBI_Dsed
M_Dsed_GBI	=	1.73E+02	=	M_Tsed_Dsed
M_Tsed_Dsed	=	1.73E+02	=	M_Lwat_Tsed
M_Tsed_Lwat	=	1.97E+00	=	M_Dsed_Tsed
M_Lwat_Tsed	=	1.73E+02	=	M_Tsed_Lwat+M_Catch_Lwat+M_ATM_Lwat
M_GBI_Dsed	=	1.97E+00	=	alphaDSed*F_GBI_Dsed

Contaminant transfers: iodine-129

lambda_Dsed_Tsed	=	1.44E-04	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Dsed	=	9.57E-05	=	(F_Tsed_Dsed + KTSed*M_Tsed_Dsed)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Tsed_Lwat	=	1.82E-02	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_Tsed	=	1.17E-02	=	(F_Lwat_Tsed + KLWat*M_Lwat_Tsed)/VLWat
lambda_Lwat_EcoOutflow	=	1.42E+00	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat

BRH_x_WNS_3000 AD

Acatch	36341		vGbi	0.059	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	7.4	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	3099	3099	3099	1	13632	13632	13632	13632	m2
Vi	22622.7	309.9	619.8	1	97468.8	2044.8	1363.2	1.3632E-08	m3
alphai	0.002	0.002	0.002	0	0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6	0	0	0.3	0.3	0.3	0.9	-
li	7.3	0.1	0.2	1	7.15	0.15	0.1	1E-12	m
Rhoi	2650	2650	0	0	2650	2650	2650	2650	kg m-3

Water fluxes

F_ATM_Catch	=	2.18E+04	=	dppt*ACatch
F_ATM_Lwat	=	1.86E+03	=	dppt*ALWat
F_ATM_Tsoil	=	8.18E+03	=	dppt*ATsoil
F_Catch_Tsoil	=	3.63E+03	=	F_ATM_Catch-F_Catch_ATMOut
F_Catch_ATMOut	=	1.82E+04	=	dETp*ACatch
F_Dsed_Tsed	=	5.18E+03	=	F_GBI_Dsed+F_Q_Dsed
F_Tsed_Lwat	=	5.18E+03	=	F_Dsed_Tsed
F_Lwat_ATMOut	=	1.55E+03	=	dETp*ALWat
F_Lwat_EcoOutflow	=	5.49E+03	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_GBI_Dsed	=	1.83E+02	=	ADSed*vGBI*SIN(phiGBI)
F_Q_Dsed	=	5.00E+03	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q
F_Q_Dsoil	=	1.36E+03	=	dcapil*AQ
F_Dsoil_Q	=	6.36E+03	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	1.36E+03	=	dcapil*ADSoil
F_Tsoil_Dsoil	=	6.36E+03	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut
F_Tsoil_ATMOut	=	6.82E+03	=	dETTSoil*ATsoil

Solid fluxes

M_ATM_Lwat	=	3.10E+01	=	mdep*ALWat
M_ATM_Tsoil	=	1.36E+02	=	mdep * ATsoil
M_Catch_Tsoil	=	3.63E+00	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil
M_Dsed_Tsed	=	1.40E+02	=	M_Q_Dsed+M_GBI_Dsed
M_Dsed_GBI	=	1.71E+02	=	M_Tsed_Dsed+M_GBI_Dsed+M_Q_Dsed-M_Dsed_Tsed
M_Tsed_Dsed	=	1.71E+02	=	M_Dsed_Tsed+M_Lwat_Tsed-M_Tsed_Lwat
M_Tsed_Lwat	=	1.40E+02	=	M_Dsed_Tsed
M_Lwat_Tsed	=	1.71E+02	=	M_ATM_Lwat+M_Tsed_Lwat
M_GBI_Dsed	=	3.66E-01	=	alphaDSed*F_GBI_Dsed
M_Q_Dsed	=	1.40E+02	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q
M_Q_Dsoil	=	1.36E+00	=	alphaQ*F_Q_Dsoil
M_Dsoil_Q	=	1.41E+02	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	2.73E+04	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_Tsoil_Dsoil	=	2.74E+04	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil

Contaminant transfers: iodine-129

lambda_Dsed_Tsed	=	4.10E-03	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Dsed	=	5.12E-04	=	(F_Tsed_Dsed + KTSed*M_Tsed_Dsed)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Tsed_Lwat	=	5.16E-01	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_Tsed	=	8.29E-02	=	(F_Lwat_Tsed + KLWat*M_Lwat_Tsed)/VLWat
lambda_Lwat_EcoOutflow	=	8.86E+00	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat
lambda_Q_Dsed	=	9.17E-04	=	(F_Q_Dsed + KQ*M_Q_Dsed)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Q_Dsoil	=	2.50E-04	=	(F_Q_Dsoil + KQ*M_Q_Dsoil)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Dsoil_Q	=	5.56E-02	=	(F_Dsoil_Q + KDSoil*M_Dsoil_Q) /(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsoil	=	1.91E-02	=	(F_Dsoil_Tsoil + KDSoil*M_Dsoil_Tsoil)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Tsoil_Dsoil	=	1.92E-02	=	(F_Tsoil_Dsoil + KTSoil*M_Tsoil_Dsoil)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))

BRH_x_SAS_4000 AD

Acatch	36341		vGbi	0.059	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	0.3	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	7.4	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1	average QD	7.4	m
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	115	115	115	1	16616	16616	16616	16616	m2
Vi	23	11.5	11.5	1E-33	106342.4	11631.2	4984.8	1.6616E-29	m3
alphai	0.002	0.002	0.002	0	0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6	0	0	0.3	0.5	0.8	0.9	-
li	0.2	0.1	0.1	1E-33	6.4	0.7	0.3	1E-33	m
Rhoi	2650	2650	0	0	2650	2650	2650	2650	kg m-3

Water fluxes

F_ATM_Catch	=	2.18E+04	=	dppt*ACatch
F_ATM_Lwat	=	6.90E+01	=	dppt*ALWat
F_ATM_Tsoil	=	9.97E+03	=	dppt*ATsoil
F_Catch_Tsoil	=	3.63E+03	=	F_ATM_Catch-F_Catch_ATMOut
F_Catch_ATMOut	=	1.82E+04	=	dETp*ACatch
F_Dsed_Tsed	=	6.28E+03	=	F_GBI_Dsed+F_Q_Dsed
F_Tsed_Lwat	=	6.28E+03	=	F_Dsed_Tsed
F_Lwat_ATMOut	=	5.75E+01	=	dETp*ALWat
F_Lwat_EcoOutflow	=	6.29E+03	=	F_ATM_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_GBI_Q	=	9.80E+02	=	AQ*vGBI*SIN(phiGBI)
F_Q_Dsed	=	6.28E+03	=	F_Dsoil_Q-F_Q_Dsoil+F_GBI_Q
F_Q_Dsoil	=	1.66E+03	=	dcapil*AQ
F_Dsoil_Q	=	6.96E+03	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	1.66E+03	=	dcapil*ADSoil
F_Tsoil_Dsoil	=	6.96E+03	=	F_ATM_Tsoil+F_Catch_Tsoil+F_Dsoil_Tsoil-F_Tsoil_ATMOut
F_Tsoil_ATMOut	=	8.31E+03	=	dETTSoil*ATsoil

Solid fluxes

M_ATM_Lwat	=	1.15E+00	=	mdep*ALWat
M_ATM_Tsoil	=	1.66E+02	=	mdep * ATsoil
M_Catch_Tsoil	=	3.63E+00	=	M_inflow_TSoil+alphaTSoil*F_Catch_Tsoil
M_Dsed_Tsed	=	1.71E+02	=	M_Q_Dsed+M_GBI_Dsed
M_Tsed_Lwat	=	1.71E+02	=	M_Dsed_Tsed
M_Lwat_EcoOutflow	=	1.72E+02	=	M_Tsed_Lwat+M_ATM_Lwat+M_Catch_Lwat
M_GBI_Q	=	9.80E-01	=	alphaQ*F_GBI_Q
M_Q_Dsed	=	1.71E+02	=	M_Dsoil_Q-M_Q_Dsoil+M_GBI_Q
M_Q_Dsoil	=	1.66E+00	=	alphaQ*F_Q_Dsoil
M_Dsoil_Q	=	1.71E+02	=	M_Q_Dsoil+M_Tsoil_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	3.32E+04	=	alphaDSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_Tsoil_Dsoil	=	3.34E+04	=	M_ATM_Tsoil+M_Catch_Tsoil+M_Dsoil_Tsoil

Contaminant transfers: iodine-129

lambda_Dsed_Tsed	=	4.94E-01	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Lwat	=	1.69E+01	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_EcoOutflow	=	5.51E+02	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat
lambda_Q_Dsed	=	1.07E-04	=	(F_Q_Dsed + KQ*M_Q_Dsed)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Q_Dsoil	=	2.81E-05	=	(F_Q_Dsoil + KQ*M_Q_Dsoil)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Dsoil_Q	=	1.51E-03	=	(F_Dsoil_Q + KDSoil*M_Dsoil_Q) /(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsoil	=	2.51E-03	=	(F_Dsoil_Tsoil + KDSoil*M_Dsoil_Tsoil)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Tsoil_Dsoil	=	9.68E-02	=	(F_Tsoil_Dsoil + KTSoil*M_Tsoil_Dsoil)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))

Bolundsfjärden FPE F1:01 – Stream with forest soils

F1_01_SFS

Acatch	120000		vGbi	5.99E-02	m/yr	sedLWatTSed	0	kg/m2/y
dETp	0.5	m/yr	PhiGbi	1.57079633	rad			
dppt	0.6	m/yr	dcapil	0.1	m/yr	sumThickAq	2.137766667	m
mDep	0.01	kg/m2/yr	mDSoil	0.1	kg m-2	sumThickTerr	2.137766667	m
mEros	0.01	kg/m2/yr	wDsoil	20	y-1			
mGbiCatch	0		dirri	0	m y-1			

	DSed	TSed	LWat	UWat	Q	DSoil	TSoil	Litt	
Ai	200	200	200		60000	60000	60000	60000	m2
Vi	417.553333	8	2		76066	42000	9000	1.20E+03	m3
alphai	0.001	0.001	0.001		0.001	0.001	0.001	0.001	kg m-3
Epsi	0.3	0.6			0.3	0.5	0.8	0.9	-
li	2.08776667	0.04	0.01		1.267766667	0.7	0.15	2.00E-02	m
Rhoi	2650	2650			2650	2650	2650	2650	kg m-3

Water fluxes

F_ATM_Catch	=	7.20E+04	=	dppt*ACatch
F_ATM_Lwat	=	1.20E+02	=	dppt*ALWat
F_ATM_Litt	=	3.60E+04	=	dppt*Alitt
F_Catch_Lwat	=	2.00E+05	=	F_inflow_LWat
F_Catch_Q	=	7.12E+03	=	(F_ATM_Catch-F_Catch_ATMOut)*lQ/sumThickTerr
F_Catch_Dsoil	=	3.93E+03	=	lDSoil/sumThickTerr*(F_ATM_Catch-F_Catch_ATMOut)
F_Catch_Tsoil	=	8.42E+02	=	(F_ATM_Catch - F_Catch_ATMOut)*lTSoil/sumThickTerr
F_Catch_ATMOut	=	6.00E+04	=	dETp*ACatch
F_Dsed_Tsed	=	3.84E+03	=	F_Catch_Dsoil*lDSed/(lLWat + lDSed + lTSed)
F_Tsed_Lwat	=	3.91E+03	=	F_Dsed_Tsed+F_Dsoil_Tsed
F_Lwat_ATMOut	=	1.00E+02	=	dETp*ALWat
F_Lwat_EcoOutflow	=	2.04E+05	=	F_Catch_Lwat+F_ATM_Lwat+F_Dsoil_Lwat+F_Tsed_Lwat-F_Lwat_ATMOut
F_GBI_Q	=	6.00E+02	=	AQ*vGBI*SIN(phiGBI)
F_Q_Dsoil	=	6.00E+03	=	dcapil*ADSoil
F_Q_EcoOutflow	=	1.46E+04	=	F_Catch_Q+F_Dsoil_Q+F_GBI_Q-F_Q_Dsoil
F_Dsoil_Dsed	=	3.84E+03	=	F_Catch_Dsoil*lDSed/(lLWat + lDSed + lTSed)
F_Dsoil_Tsed	=	7.35E+01	=	F_Catch_Dsoil*lTSed/(lLWat + lDSed + lTSed)
F_Dsoil_Lwat	=	1.84E+01	=	F_Catch_Dsoil*lLWat/(lLWat + lDSed + lTSed)
F_Dsoil_Q	=	1.28E+04	=	F_Q_Dsoil+F_Tsoil_Dsoil-F_Dsoil_Tsoil
F_Dsoil_Tsoil	=	6.00E+03	=	dcapil*ATsoil
F_Tsoil_Dsoil	=	1.28E+04	=	F_Dsoil_Tsoil+F_Catch_Tsoil+F_Litt_Tsoil-F_Tsoil_Litt
F_Tsoil_Litt	=	3.00E+04	=	dETLitt*ATsoil
F_Litt_Tsoil	=	3.60E+04	=	F_Tsoil_Litt+F_ATM_Litt-F_Litt_ATMOut
F_Litt_ATMOut	=	3.00E+04	=	dETLitt*Alitt

Solid fluxes

M_ATM_Catch	=	1.20E+03	=	mdep*ACatch
M_ATM_Litt	=	6.00E+02	=	mdep*Alitt
M_Catch_Lwat	=	1.40E+03	=	meros*ACatch+M_inflow_LWat
M_Catch_Q	=	7.12E+00	=	alphaQ*((F_ATM_Catch-F_Catch_ATMOut)*lQ/sumThickTerr)
M_Catch_Dsoil	=	3.93E+00	=	alphaDSoil*((F_ATM_Catch-F_Catch_ATMOut)*lDSoil/sumThickTerr)
M_Catch_Tsoil	=	8.42E-01	=	alphaTSoil*(F_ATM_Catch-F_Catch_ATMOut)*lTSoil/sumThickTerr
M_Dsed_Tsed	=	1.80E+03	=	M_Tsed_Dsed+M_Dsoil_Dsed
M_Tsed_Dsed	=	1.80E+03	=	meros*(ATsoil+ACatch)
M_Tsed_Lwat	=	1.80E+03	=	M_Dsed_Tsed+M_Dsoil_Tsed+M_Lwat_Tsed-M_Tsed_Dsed
M_Lwat_Tsed	=	1.80E+03	=	meros*(ATsoil+ACatch)
M_Lwat_EcoOutflow	=	2.00E+03	=	M_Catch_Lwat+M_Tsed_Lwat+M_Dsoil_Lwat+M_Tsoil_Lwat-M_Lwat_Tsed
M_GBI_Q	=	6.00E-01	=	alphaQ*F_GBI_Q
M_Q_Dsoil	=	6.00E+00	=	alphaQ*F_Q_Dsoil
M_Q_EcoOutflow	=	8.56E+00	=	M_Catch_Q+M_GBI_Q+M_Dsoil_Q-M_Q_Dsoil
M_Dsoil_Dsed	=	3.84E+00	=	alphaDSoil*F_Dsoil_Dsed
M_Dsoil_Tsed	=	7.35E-02	=	alphaDSoil*F_Dsoil_Tsed
M_Dsoil_Lwat	=	1.84E-02	=	alphaDSoil*F_Dsoil_Lwat
M_Dsoil_Q	=	6.84E+00	=	M_Tsoil_Dsoil+M_Q_Dsoil-M_Dsoil_Tsoil
M_Dsoil_Tsoil	=	1.20E+05	=	alphaTSoil*F_Dsoil_Tsoil+wDsoil*mDSoil*ADSoil
M_Tsoil_Lwat	=	6.00E+02	=	meros*ATsoil
M_Tsoil_Dsoil	=	1.20E+05	=	M_Catch_Tsoil+M_Litt_Tsoil+M_Dsoil_Tsoil-M_Tsoil_Litt-M_Tsoil_Lwat
M_Tsoil_Litt	=	3.00E+01	=	alphaTSoil*F_Tsoil_Litt
M_Litt_Tsoil	=	6.30E+02	=	M_Tsoil_Litt+M_ATM_Litt

Contaminant transfers: iodine-129

lambda_Dsed_Tsed	=	1.88E-02	=	(F_Dsed_Tsed + KDSed*M_Dsed_Tsed)/(VDsed*(thetaDSed + (1 - epsDSed)*rhoDSed*KDSed))
lambda_Tsed_Dsed	=	2.08E-01	=	(F_Tsed_Dsed + KTSed*M_Tsed_Dsed)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Tsed_Lwat	=	1.53E+01	=	(F_Tsed_Lwat + KTSed*M_Tsed_Lwat)/(VTsed*(thetaTSed + (1 - epsTSed)*rhoTSed*KTSed))
lambda_Lwat_Tsed	=	2.70E+02	=	(F_Lwat_Tsed + KLWat*M_Lwat_Tsed)/VLWat
lambda_Lwat_EcoOutflow	=	1.02E+05	=	(F_Lwat_EcoOutflow + KLWat*M_Lwat_EcoOutflow)/VLWat
lambda_Q_Dsoil	=	1.42E-04	=	(F_Q_Dsoil + KQ*M_Q_Dsoil)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Q_EcoOutflow	=	3.44E-04	=	(F_Q_EcoOutflow + KQ*M_Q_EcoOutflow)/(VQ*(thetaQ + (1 - epsQ)*RhoQ*KQ))
lambda_Dsoil_Dsed	=	2.30E-04	=	(F_Dsoil_Dsed + KDSoil*M_Dsoil_Dsed)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsed	=	4.40E-06	=	(F_Dsoil_Tsed + KDSoil*M_Dsoil_Tsed)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Lwat	=	1.10E-06	=	(F_Dsoil_Lwat + KDSoil*M_Dsoil_Lwat)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Q	=	7.68E-04	=	(F_Dsoil_Q + KDSoil*M_Dsoil_Q) /(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Dsoil_Tsoil	=	2.51E-03	=	(F_Dsoil_Tsoil + KDSoil*M_Dsoil_Tsoil)/(VDsoil*(thetaDSoil + (1 - epsDSoil)*rhoDSoil*KDSoil))
lambda_Tsoil_Lwat	=	1.21E-04	=	(F_Tsoil_Lwat + KTSoil*M_Tsoil_Lwat)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))
lambda_Tsoil_Dsoil	=	1.11E-01	=	(F_Tsoil_Dsoil + KTSoil*M_Tsoil_Dsoil)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))
lambda_Tsoil_Litt	=	2.02E-01	=	(F_Tsoil_Litt + KTSoil*M_Tsoil_Litt)/(VTsoil*(thetaTSoil + (1 - epsTSoil)*rhoTSoil*KTSoil))
lambda_Litt_Tsoil	=	3.59E+00	=	(F_Litt_Tsoil + KLitt*M_Litt_Tsoil)/(VLitt*(thetaLitt + (1 - epsLitt)*rhoLitt*KLitt))

SSI report

STATENS STRÅLSKYDDSINSTITUT, SSI, är en central tillsynsmyndighet som verkar för ett gott strålskydd för människan och miljön, nu och i framtiden.

SSI sätter gränser för stråldoser till allmänheten och för dem som arbetar med strålning, utfärdar föreskrifter och kontrollerar att de efterlevs. SSI håller beredskap dygnet runt mot olyckor med strålning. Myndigheten informerar, utbildar och utfärdar råd och rekommendationer samt stöder och utvärderar forskning. SSI bedriver även internationellt utvecklingssamarbete.

Myndigheten, som sorterar under Miljödepartementet, har 110 anställda och är belägen i Solna.

THE SWEDISH RADIATION PROTECTION AUTHORITY (SSI) is a central regulatory authority charged with promoting effective radiation protection for people and the environment today and in the future.

SSI sets limits on radiation doses to the public and to those that work with radiation. SSI has staff on standby round the clock to respond to radiation accidents. Other roles include information, education, issuing advice and recommendations, and funding and evaluating research.

SSI is also involved in international development cooperation. SSI, with 110 employees located at Solna near Stockholm, reports to the Ministry of Environment.

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Adress: Statens strålskyddsinstitut; S-171 16 Stockholm
Besöksadress: Solna strandväg 96
Telefon: 08-729 71 00, Fax: 08-729 71 08

Address: Swedish Radiation Protection Authority
SE-171 16 Stockholm; Sweden
Visiting address: Solna strandväg 96
Telephone: + 46 8-729 71 00, Fax: + 46 8-729 71 08
www.ssi.se