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Further modelling and sensitivity study using the GEMA-Site "alternative biosphere models" and review of material from SKB's RFI response

Main Review Phase

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information och göra expertbedömningar i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Det övergripande syftet med projektet är att utföra modellerings jämförelser mellan alternativa biosfärsmodeller och SKB:s LDF modeller för att undersöka osäkerheten i nyckelparametrar, huvudsakligen flödesfaktorer, objekts storlek och alternativa datavärden för K_d och CR.

Författarens sammanfattning

Denna rapport har upprättats som en del av SSM:s huvudgranskning av SKB:s säkerhetsanalys av den långsiktiga säkerheten för KBS-3 (SR-Site), en geologisk slutförvarsanläggning, som SKB planerar uppföra i Forsmark. Granskningen tar upp de metoder som används för dosberäkningar i SR-Site, speciellt vad gäller transporter, ackumulering och överföring av radionuklider i ytnära miljö och på vilka sätt doser till framtida populationer av människor och djur kan uppstå.

Tidigare forsknings- och granskningsrapporter (Kłos, m.fl., 2014a; Kłos och Wörman, 2015) har fokuserat på den metod som SKB valt för att modellera radionuklidtransport och ackumulation i biosfären och har även beskrivit utvecklingen och tillämpningen av en alternativ dosmodell - GEMA-Site som utformades för att matcha kapaciteten hos SKB:s SR-Site modell som används för att generera s.k. Landskap Dos Faktorer (LDF). LDF används av SKB för att skala utsläpp från geosfären för att uppskatta potentiella framtida radiologiska effekter av utsläppen från det planerade slutförvaret.

Denna rapport fokuserar på tre frågor i detalj:

- Den tidigare granskningen (Kłos, m.fl., 2014a) ledde till att SSM skickade en begäran om ytterligare information (RFI) till SKB för att få klargörande detaljer om SR-Site modelleringen. SKB:s svar på dessa RFI granskas här.
- Tillämpningen av GEMA-Site i en känslighetsanalys för att bestämma vilka de viktigaste parametrarna är som påverkar dosen i biosfärsmodelleringen.
- Jämförelse av resultat från GEMA-Site med de numeriska resultaten från SR-Site LDF.

RFI formulerades med avsikten att informationen skulle kunna användas för att bättre karaktärisera hydrologiutvecklingen i bassänger som sannolikt kommer att utvecklas i det framtida Forsmarkslandskapet. Radionuklidtransportmodellen i SR-Site bygger på en genomsnittlig hydrologi baserad på hydrologin i sex sjöar i dagens terrestra biosfär, och på uppskattade flöden år 5000 AD framtagna utifrån resultat från MIKE-SHE modellering.

Den begärda kompletterade informationen besvarade de flesta frågorna, men analysen av flödessystemen för de sex sjöarna vid tidpunkterna 2000, 3000 respektive 5000 AD gav inte någon tydlig bild av hur hydrologin utvecklas i systemet. I rapporten konstateras därför att tillgång till MIKE-SHE resultat på djupare nivå behövs för att bättre kunna formulera en adekvat representation av utvecklingen av hydrologin i systemet.

GEMA-Site modellen har använts för att utföra en serie känslighetsanalyser. Analyserna (PSA) har genomförts med hjälp av sannolikhetsfördelningsfunktioner från SR-Site dokumentationen med information om fysiska egenskaper hos aktuell bassäng tolkade utifrån den platsbeskrivande modelleringen i SR-Site.

Slutsatserna från den här sista delen av huvudgranskningen är:

1. Kombinationen av de sex olika sjöarna i SR-Site för att generera ett ”genomsnittligt objekt” är varken försvarbar eller reproducerbar;
2. Resultat från känslighetsanalysen visar att bassängernas geometri spelar en stor roll för dosuppskattningen;
3. Bättre integration av detaljer i grundvattenmodelleringen (till exempel med hjälp av MIKE-SHE) krävs för att radionuklidtransportmodellen ska ge en mer rättvisande och fullständig beskrivning av viktiga delar av hydrologin som påverkar dos;
4. De statistiska resultaten från tillämpningen av GEMA-Site tyder på att LDF för radionuklider med låga k_d värden sannolikt inte kommer att vara underskattade men att LDF för radionuklider med högre k_d värden, särskilt de i ^{226}Ra kedjan (inklusive ^{210}Pb och särskilt ^{210}Po) kan vara underskattade, potentiellt några storleksordningar, beroende på antaganden om exploatering av lokala vattenresurser.
5. De LDF värden som redovisas i SR-Site är lämpliga för det ändamål som de är avsedda för. Men det finns reservationer beträffande LDF värden för radionuklider med högre k_d värden och de är relaterade till tolkningen av hydrologin i bassängen (inklusive antaganden om vattenanvändning). Framtida säkerhetsutvärderingar bör använda en förbättrad tolkning av vattenflöden och det bör finnas en bättre integrering av resultaten från MIKE-SHE liknande modeller.

Projekt information

Kontaktperson på SSM: Shulan Xu

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information and provide expert opinion on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The general objective of the project is to perform modelling comparison between alternative biosphere models an SKB's LDF modelling approach to explore uncertainties in key parameters, mainly, flow scaling factors, basin size, and alternative data values for K_ds and CRs.

Summary by the author

This report has been prepared as part of the SSM's Main Review Phase of SKB's SR-Site performance assessment of the long-term safety of the KBS-3 geological disposal facility (GDF) proposed for construction at Forsmark. The review addresses the methodology employed in the dose assessment calculations of SR-Site; specifically issues of transport, accumulation and transfers of radionuclides in the near surface environment and the way in which doses to future human and non-human populations can arise.

Earlier reports have focussed on the approach taken by SKB to model radionuclide transport and accumulation in the biosphere and have described the development and application of an alternate dose assessment model – GEMA-Site – designed to match the capabilities of the SR-Site dose assessment model as used to generate the Landscape Dose Factors (LDFs) that SKB use to scale release from the geosphere in order to estimate potential future radiological impact of the release from the planned repository.

This final report considers three issues in greater detail

- The earlier review prompted the SSM review team to send Requests for Further Information (RFIs) to SKB in order to clarify details of the SR-Site modelling. SKB's response to these RFIs is reviewed here.
- The application of GEMA-Site in a sensitivity analysis to determine the key parameters influencing dose in the biosphere dose assessment.
- Comparison of results from GEMA-Site with the numerical results SR-Site LDFs.

The RFIs were formulated with the intention of used the response to better characterise the evolving hydrology within basins likely to develop in the future Forsmark landscape. The SR-Site radionuclide transport model is based on an average of the hydrology of six lakes in the present-day terrestrial biosphere, using fluxes estimated at the year 5000 CE in results from the MIKE-SHE hydrological modelling code.

Most of the requested details were forthcoming but analysis of the flow systems for the six lakes at each of 2000, 3000 and 5000 CE did not provide a clear indication of the evolution of the system. It was concluded that access to the deeper level MIKE-SHE results is needed to better formulate an adequate representation of the evolving system.

The GEMA-Site model was used to carry out a series of probabilistic sensitivity. The analyses (psa) were executed using probability distribution functions from the SR-Site documentation with details of physical characteristics of the basin interpreted from the site-descriptive modelling in SR-Site.

Conclusions from this final part of the main phase review study are:

1. The combination of the six different lakes in SR-Site to generate an "average object" is neither justifiable nor reproducible;
2. Results from the sensitivity analysis indicate that the geometry of basins plays a large role in determining dose;
3. Better integration of details of groundwater modelling (for example, using MIKE-SHE) is required so that the radionuclide transport model provides a more accurate and comprehensive expression of key parts of the hydrology that influence dose;
4. The statistical results from the application of GEMA-Site suggest that the LDFs for low k_d radionuclides are not likely to be underestimates but that doses from higher k_d radionuclides, particularly the ^{226}Ra chain (including ^{210}Pb and ^{210}Po explicitly) might be underestimates, potentially by some orders of magnitude, depending on assumptions for exploitation of local water resources.
5. The LDFs reported in SR-Site are suitable for the purpose for which they are intended. There are reservations concerning the LDFs for higher k_d radionuclides and these are related to the interpretation of basin hydrology (including assumptions for water usage). Future assessments should use an improved interpretation of water fluxes and there should be better integration of results from MIKE-SHE=class models.

Project information
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Contents

1. Introduction

In 2011 the Swedish Nuclear Fuel and Waste Management Company (SKB) submitted an assessment of the long-term safety of a KBS-3 geological disposal facility (GDF) for the disposal of spent nuclear fuel and high level radioactive waste in Forsmark, Sweden. This assessment, the SR-Site project, supports the licence application of SKB to build such a final disposal facility.

The initial phase of SSM's review of SR-Site by the Swedish Nuclear Fuel and Waste Management Company (SKB) was completed at the end of 2013. SSM concluded that SKB's reporting was sufficiently comprehensive and of sufficient quality to justify a continuation of SSM's review to the main review phase. While the overall goal of the initial review phase was to identify issues for deeper review with a broad coverage of SKB's safety assessment, assignments carried out during the main review phase are targeted on tasks and issues prioritized by SSM with the intention to indirectly or directly support SSM's compliance judgements. This includes detailed analysis of a range of specific issues for which SSM has judged that further input from SSM's external experts would be helpful.

The task reported here constitutes a further and deeper evaluation of the suitability of SKB's biosphere dose assessment model through comparison with the alternative biosphere modelling approach developed in the preliminary stage (Kłos *et al*., 2014a). Both analysis and review have been undertaken as part of the task. The analysis involved implementation of the GEMA-Site alternative biosphere dose assessment model (Kłos, 2015) that focused on alternate interpretations of the most important transport and accumulation processes. This is carried out as a sensitivity study to determine the model parameters having the most impact on the Landscape Dose Factor (LDF) used by SKB to determine the radiological impact of release to the biosphere in SR-Site.

The review element of this task involves an interpretation of the information requested from SKB by SSM at the end of the initial phase of the review. This material concerns interpretation of the hydrological parameterisation of surface water flows in the regolith in the Forsmark region. Material in the relevant SR-Site reports:

- Landscape dose model – SKB report TR-10-06 (Avila *et al*., 2010)
- Element and radionuclide specific data, SKB Report TR-10-07 (Nordén *et al*., 2010),
- Terrestrial ecosystems description – SKB Report TR-10-01; Löfgren, 2010,
- Limnic ecosystems description – SKB Report TR-10-02; Andersson, 2010,
- Landscape description – SKB Report TR-10-05 (Lindborg, 2010) and
- Surface hydrological description – SKB Report R-10-02 (Bosson *et al*., 2010)

was found to be insufficient and a detailed Request for Further Information (RFI) was submitted to SKB. Appendix 1 lists the RFI and appendix 2 is a compilation and summary if SKBs response. Accordingly, the material reported here is broken down as follows.

- Chapter 2 – Review and discussion of SKB's RFI response
- Chapter 3 – Summary and conceptual discussion of the GEMA-Site (alternate) model used in the probabilistic sensitivity study reported in Chapter 4, including a description of the updates required for the probabilistic modelling

- Chapter 4 – Results and discussion of the sensitivity study carried out using the GEMA-Site model
- Chapter 5 brings together the elements of the review to assess the potential uncertainty in the calculated LDFs and discusses the sources if uncertainty.

Focus here is upon four of the five radionuclides which contributed most to the calculated annual effective human dose presented by SR-Site for the shear failure scenario (SKB, 2011): ^{79}Se, ^{94}Nb, ^{129}I and ^{226}Ra. (the fifth - ^{14}C is reviewed separately as the modelling approach used is less dependent on the hydrological interpretation of the sites.)

Overall conclusions of this main phase of the review are given in Chapter 6.

2. Requests for Further Information and SKB's response

2.1. Summary of requirements

The near surface hydrology is the main driver of the radionuclide transport model. The parametrisation of the hydrological description in Bosson *et al*., (2010) was based on detailed MIKE-SHE modelling of past, present and future conditions at the site. Data from six lakes in the present-day terrestrial landscape were then used to determine the characteristics "average object" in the landscape that was carried forward to the parameterisation used in the Avila *et al*. radionuclide transport model. Although details for "snapshots" of the hydrology at several timepoints were available, the flux map used in the transport calculations used only the results at 5000 CE.

Bosson *et al*. (2010) is a comprehensive report, including some description of the MIKE-SHE model. Given the scope of the main-phase review, however, the focus has been on understanding the origin of details translated to the dose assessment modelling. In terms of the structure of Bosson *et al*., this means that the discussions in Chapter 8, detailing the information delivered to the dose calculations has been of prime concern. It is here that the definition of the average lake-mire object is presented. The detailed MIKE-SHE results (Chapters 5 to 7) have, consequently, received less attention.

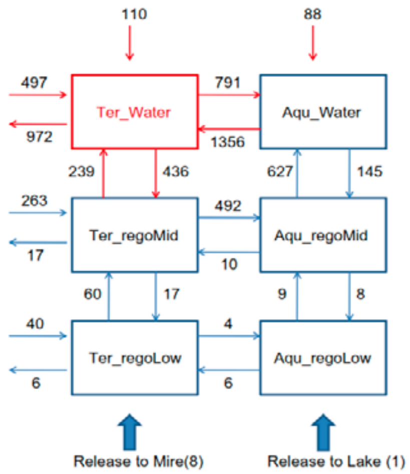
Nevertheless, there is a great deal of information potentially available from the MIKE-SHE modelling. Water balance for each of the six lakes used to describe the "average object" could have been evaluated at any time. It is implicit that similar information could have been provided for any basin at any time but that only results these six lakes and the three times had been calculated and so were readily available for further investigation.

The request for the water fluxes for each of the six lakes at three times was intended to allow the evolutionary sequence of the different lakes to be understood and to determine if the six lakes were sufficiently representative that the "average object" had practical utility in describing features in the landscape. The requests set out in Appendix 1, and the response (Appendix 2) were only partially successful in this. Nevertheless some useful insight into the translation of site-descriptive detail into the dose assessment model has been gained.

2.2. Interpretation of SKB's RFI response

2.2.1. Parameterisation of water fluxes

The justification for the parameterisation of key water fluxes in the radionuclide transport model was raised in the first part of the main phase review (Kłos *et al*., 2014a). The request for detailed reasoning behind the parameterisation was not answered in the RFI response. The response stated that a detailed response would be provided by September 2014. At time of completing this report the material has not been forthcoming. Confidence in the SR-Site radionuclide transport model is therefore not as high as might be.



(a) SR-Site model, taken from TR-10-06 (Avila *et al*. (2010)

	geosphere	sub-catchment	Ter_regoLow	Ter_regoMid	Ter_Water	Aqu_regoLow	Aqu_regoMid	Aqu_Water	Atm	Down-stream
geosphere			7			3				
sub- catchment			40	263	497					
Ter_ regoLow				60		4				6
Ter_ regoMid			17		239		492			17
Ter_ Water				436				791		972
Aqu_ regoLow			6				9			
Aqu_ regoMid				10		8		627		
Aqu_ Water					1356		145			
Atm					110			88		
Upstream										
Inflow	0.0	0.0	70.0	769.0	2202.0	15.0	646.0	1506.0	0.0	995.0
Outflow	10.0	800.0	70.0	765.0	2199.0	15.0	645.0	1501.0	198.0	0.0
Balance	-10.0	-800.0	0.0	4.0	3.0	0.0	1.0	5.0	-198.0	995.0

(b) Excel implementation of the same data showing mass balance

	geosphere	sub-catchment	Ter_regoLow	Ter_regoMid	Ter_Water	Aqu_regoLow	Aqu_regoMid	Aqu_Water	Atm	Down-stream
geosphere			8.5			1.0				
sub- catchment			40.0	487.7	603.0					
Ter_ regoLow				66.7		4.0				11.5
Ter_ regoMid			27.5		400.3		544.8			27.5
Ter_ Water				441.3				729.2		1275.5
Aqu_ regoLow			6.0				7.7			
Aqu_ regoMid				5.2		8.7		649.5		
Aqu_ Water					1320.3		110.7			
Atm					137.7			61.8		
Upstream										
Inflow	0.0	0.0	82.0	1000.8	2461.3	13.7	663.2	1440.5	0.0	1314.5
Outflow	9.5	1130.7	82.2	1000.2	2446.0	13.7	663.3	1431.0	199.5	0.0
Balance	-9.5	-1130.7	-0.2	0.7	15.3	0.0	-0.2	9.5	-199.5	1314.5

(c) Average for the six lakes at 5000 CE

Figure 1: Water fluxes maps for the representative object in the SR-Site radionuclide transport model. "Average object" derived by Bosson *et al.* (2010). The Excel format illustrates balance for each of the compartments in the model's structure. Also shown is the same scheme derived from the average of the six lakes at 5000 CE (See Appendix 2).

2.2.2. Reconstructing the "average object" fluxes

Water fluxes in the TR-10-06 radionuclide transport model (Avila *et al*. 2010) are all quoted in terms of mm year^{-1}. The water fluxes used in the transport model are illustrated in Figure 1, as taken from Bosson *et al*. (2010) with the reconfiguration into Excel so as to better illustrate mass balance in the modelled system. Also illustrated is the same detail translated to Excel to assess mass balance in the average object".

The “average object” is reported as having been generated by combining the velocities generated by the MIKE-SHE mass balance tool from the six objects cited in Appendices 1 and 2 at 5000 CE to give an average scheme (page 304 of Bosson *et al*.). This is then assumed to be representative of objects in the landscape as a whole. Figure 1 also shows the balance scheme for the average of the six objects at 5000 CE using the data in SKB’s response. There are noticeable differences in the numerical values and while the balance figures used by SKB are not perfect, the combined results from Appendix 2 where the SKB data have been reanalysed for this report, are further from balance. It has not been possible to reproduce the numerical details of the water balance in the “average object” as used in SR-Site. The method used to produce the “average object” remains obscure.

2.2.3. Evolution of ecosystems – areas within the basin

A criticism of the approach taken by SKB to modelling the hydrology of basins in the future landscape is that the flux maps (such as Figure 1) do not change as the system evolves. This is potentially a key difference between the SKB radionuclide transport model and GEMA-Site. One of the aims of the RFIs was to understand the evolution of the system both in terms of water fluxes as well as changes to the areas within the basins that are classed as terrestrial and aquatic ecosystems.

Figure 1 illustrates that the SKB approach used *advective velocities* rather than fluxes. Kłos *et al*. (2014a) noted the importance of understanding the fluxes and the areas involved. This was the reason for the request that both velocities *and* fluxes be provided. Also requested were details of how the terrestrial and aquatic areas changed as the lake/mire system evolved.

Although the Request 1 clearly stated that areas of catchment, lake, mire and lake + mire should be provided at the three times 2000 CE, 3000 CE and 5000 CE, data for only a single time were provided (2010 CE), as were reported in the original Bosson *et al*. report. This suggests either that the information was not available or that the areas did not change significantly during the relatively short period from 2000 CE to 5000 CE. Nevertheless, since the velocities and fluxes are related by $F_{ij} = A_{norm} v_{ij}$, the normalising area between each compartment can be found. Using the flux and velocity maps shown at the end of Appendix 2 it is possible to determine how the terrestrial and aquatic areas change in time for each of the six lakes. To do so requires setting some rules-of-engagement, concerning what may be assumed:

1. Each basin in the landscape is defined by its topographic boundary. Effectively this boundary is the watershed between basins. Sedimentation does not change the boundaries between basins. The total area of each of the basins is constant.
2. Precipitation (P) and evapotranspiration (E) in the calculations are constant are 560 mm year^{-1} and 410 mm year^{-1} respectively. The values in the Chapter 8 of Bosson *et al*. (2010) are P = 560 mm year^{-1}, E = 400 to 410 mm year^{-1} and these are the values used here. Net “runoff” (the difference $P – E$) is 150 to 160 mm year^{-1}. In the regional groundwater modelling with MIKE-SHE the values were

583 and 410 mm year^{-1}. The reason for this difference is not immediately clear and it may also be noted that the net infiltration at the surface of the terrestrial and aquatic objects in Figure 1 does not correspond to any of the figures. This is why working with volumetric fluxes is more reliable and transparent.

3. Total inflow to terrestrial side is runoff from outer basin (sub-catchment):

$$F_{totTer,in} = \left(F_{\substack{subCatch \\ terLow}} + F_{\substack{subCatch \\ terMid}} + F_{\substack{subCatch \\ terWat}} \right) = (P - E)\, A_{subCatch}$$

   Referring to Figure 1, the terrestrial and aquatic areas are explicit (with surface areas $A_{terrWat}$ m^2 and A_{aquWat} m^2 respectively. These areas correspond broadly to wetland and lake ecosystems at the lower elevations of the basin's topography. Implicit therefore is the area of the rest of the basin – the sub-catchment in SKB's terminology, with area $A_{subCatch}$ m^2. The total accumulated infiltration in the sub-catchment is conserved and partitioned into flows to the terrestrial lower, mid- and upper regolith compartments.

4. Input to terrestrial and aquatic water reflects difference in area,
   $F_{\substack{atm \\ terrWat}} = (P - E)\, A_{terrWat}$, $F_{\substack{atm \\ aquWat}} = (P - E)\, A_{aquWat}$

5. As a compartment description, the "average object" model implies a similar relation for the base of the regolith:

$$F_{\substack{geo \\ terLow}} = v_{geo} A_{terrWat} \,,\; F_{\substack{geo \\ aquLow}} = v_{geo} A_{aquWat} \,,$$

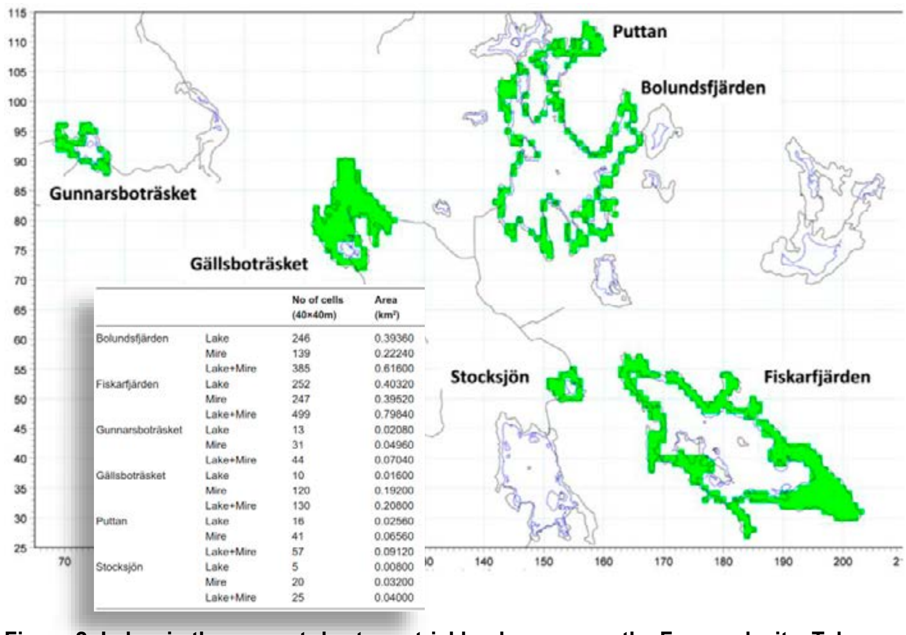
   where the advective velocity at the base of the basin is v_{geo} mm year^{-1}.

6. Since

$$\begin{aligned} F_{loss} &= F_{\substack{geo \\ terLow}} + F_{\substack{geo \\ aquLow}} + F_{subCatch} + F_{\substack{atm \\ aquWat}} + F_{\substack{atm \\ terWat}} \\ &= (P - E)\, A_{basin} + F_{\substack{geo \\ terLow}} + F_{\substack{geo \\ aquLow}} \end{aligned} ,$$

   the total basin area is given by

$$A_{basin} = \frac{F_{loss} - F_{\substack{geo \\ terLow}} - F_{\substack{geo \\ aquLow}}}{P - E} .$$



		No of cells (40×40m)	Area (km²)
Bolundsfjärden	Lake	246	0.39360
	Mire	139	0.22240
	Lake+Mire	385	0.61600
Fiskarfjärden	Lake	252	0.40320
	Mire	247	0.39520
	Lake+Mire	499	0.79840
Gunnarsboträsket	Lake	13	0.02080
	Mire	31	0.04960
	Lake+Mire	44	0.07040
Gällsboträsket	Lake	10	0.01600
	Mire	120	0.19200
	Lake+Mire	130	0.20800
Puttan	Lake	16	0.02560
	Mire	41	0.06560
	Lake+Mire	57	0.09120
Stocksjön	Lake	5	0.00800
	Mire	20	0.03200
	Lake+Mire	25	0.04000

Figure 2: Lakes in the present-day terrestrial landscape near the Forsmark site. Taken from Bosson *et al.*, Figure 8-3, with (inset) area data taken from Table 8-1.

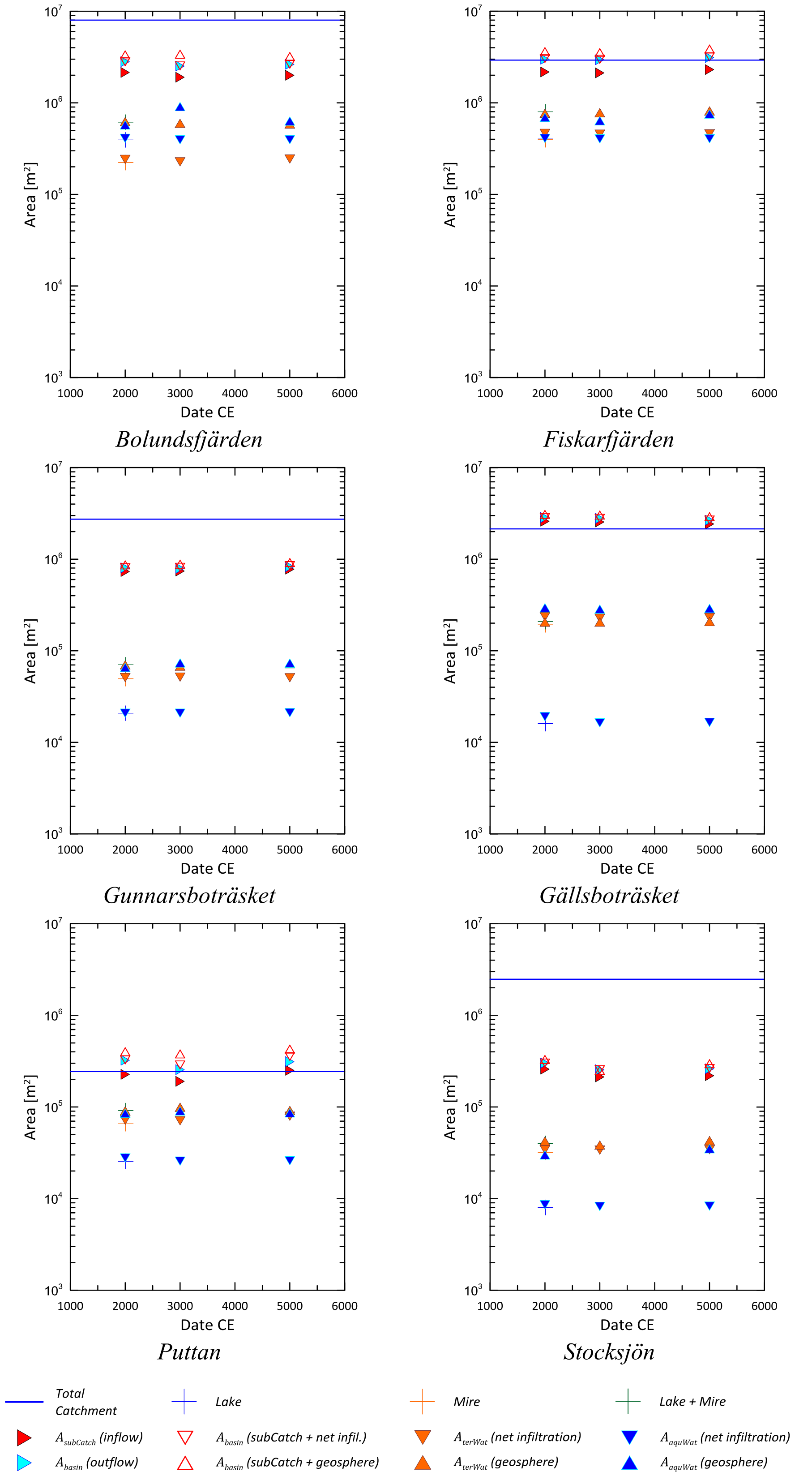


Figure 3: Comparison of derived areas for the six lakes at three times. also shown are the figures cited in Avila *et al.* (2010) for total catchment and lake, mire and lake + mire.

This method allows all the areas to be estimated and also allows for consistency checks. The lakes included in the definition of “average hydrology” are shown in Figure 2. Figure 3 illustrates the calculated areas for terrestrial, aquatic and terrestrial and aquatic combined. As these are derived from fluxes at both the upper and lower boundaries, a range is implied. The derived values are compared with the numerical values taken from Bosson *et al*. (2010).

Given the multiple steps separating the MIKE-SHE *details* and the derivation of areas, the results are informative. Three of the lakes have total catchment and derived basin sizes broadly consistent (*Fiskarfjärden*, *Gällsboträsket*, *Puttan*) and three have Total Catchment > derived basin size (*Bolundsfjärden*, *Gunnarsboträsket*, S*tocksjön*).

The “good” lakes, where the estimated basin area is similar to the quoted area, have limited upstream inflow (from outside the basin), *Puttan* & *Fiskarfjärden* appear to have none and *Gällsboträsket* seems to have stream inputs that are likely to be small compared to the total basin. In contrast, *Bolundsfjärden* has input from both *Gällsboträsket* and *Stocksjön*, complicated by the inflow to the small *Stocksjön* being augmented by the outflow a much larger large lake (unnamed) to the southwest of *Stocksjön* itself (see Figure 2). The source of water flows into *Gunnarsboträsket* basin is not clear. Cases where the area estimated from the total throughflow is larger than the “total catchment” imply that the lake’s basin does not provide all the water discharged from the basin. In such cases the “excess” flow is in the stream discharge.

The main hope for the RFI responses was that the evolution of the flow systems for the six lakes would be discernible in the results for the three times. Figure 4 shows the evolutionary trends of the sizes of the derived areas for lake and mire. A linear fit is included. The results indicate that there is little change to the areas. Only for *Puttan* is there are clear trend (below) with the area of the wetland increasing and the area of open water decreasing. The gradients (linear fits) are, respectively, 2.7 m^2 $year^{-1}$ and -0.53 m^2 $year^{-1}$. For *Bolundsfjärden* there are small gradients: 1.7 m^2 $year^{-1}$ and -3.7 m^2 $year^{-1}$ for mire and lake respectively. These are the two lakes closest to the shoreline at 2010 CE and it might be expected that the rates of change decrease with age from isolation and with profile. The other four lakes show barely discernible gradients that, in some have, show the opposite trend to what might be expected in that the lake area increases and the mire shrinks. Clearly there are difficulties in interpreting the data as used for the lakes’ water balance.

The flux map in Figure 1 shows that SKB divide their model into aquatic and terrestrial parts. These are the parts where radionuclides released from the bedrock can accumulate and so give rise to dose. The “outer” basin (sub-catchment) is not included in this interpretation. This can be understood since any accumulations in the outer basin will be at low concentrations. Nevertheless the effect of the “outer” basin is included in that it contributes water fluxes. This is done using “normalising” factors that effectively partition the net infiltration on the outer basin between the upper and mid-regolith of the wetland.

In the GEMA-Site model all parts of the basin are explicitly included. Sub-horizontal flows from the Outer basin to the Inner basin are characterised by the partitioning factors, ϕ_i, in a similar fashion the SKB model:

$$\phi_i = \frac{F_{subCatch,i}}{\sum\limits_{i=Low,Mid,Wat} F_{subCatch,i}}$$

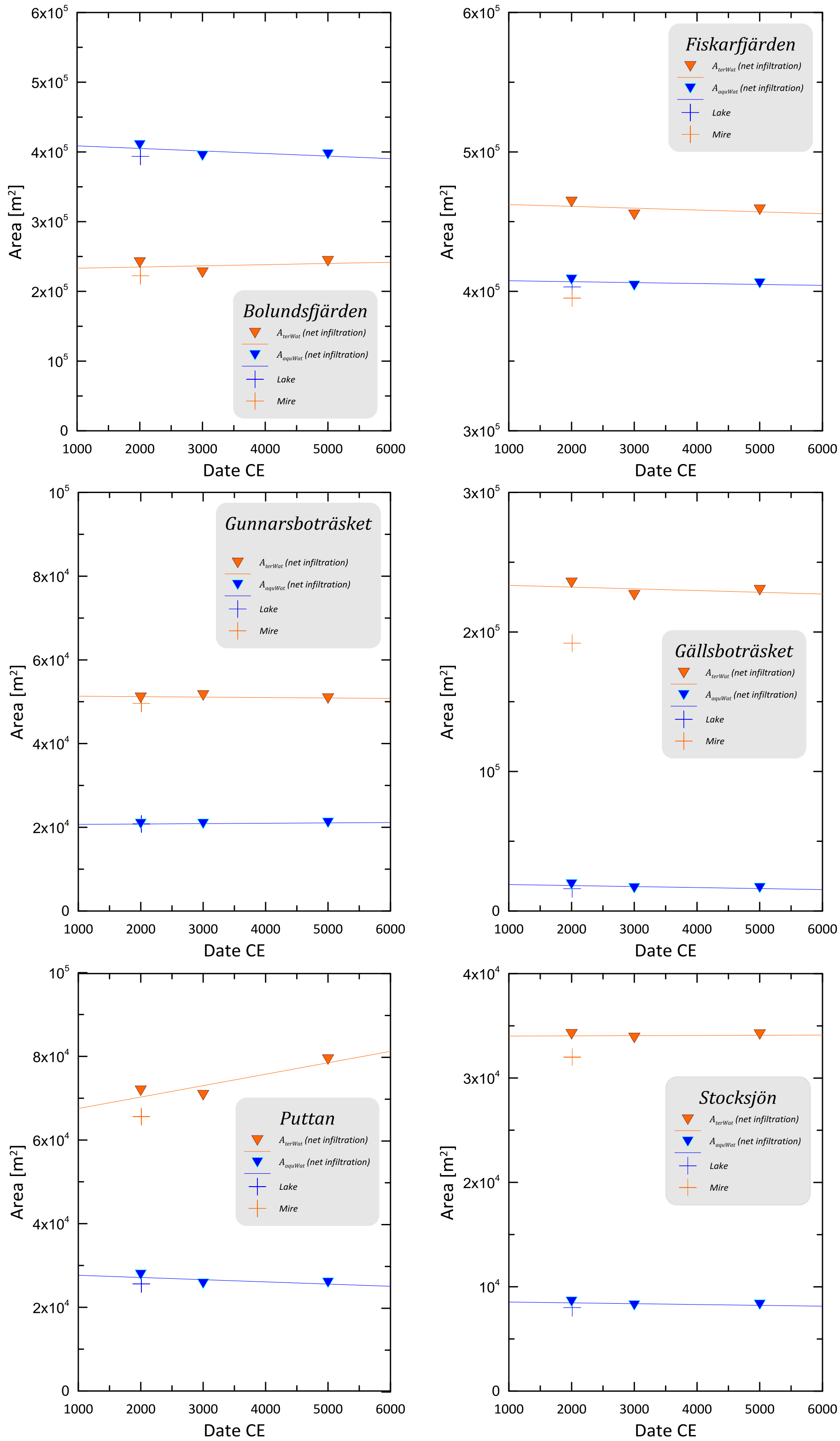


Figure 4: Estimates of changes to ecosystems areas for six lakes. Areas derived from water fluxes and water velocities supplied by SKB in response to RFI1 using the rules of engagement set out above. Also plotted are the quoted areas of the lakes at 2000 CE (Bosson *et al.*, 2010 as provided by SKB in the response to RFI1). Linear fits to the mire and lake areas are indicated to highlight trends in ecosystem development.

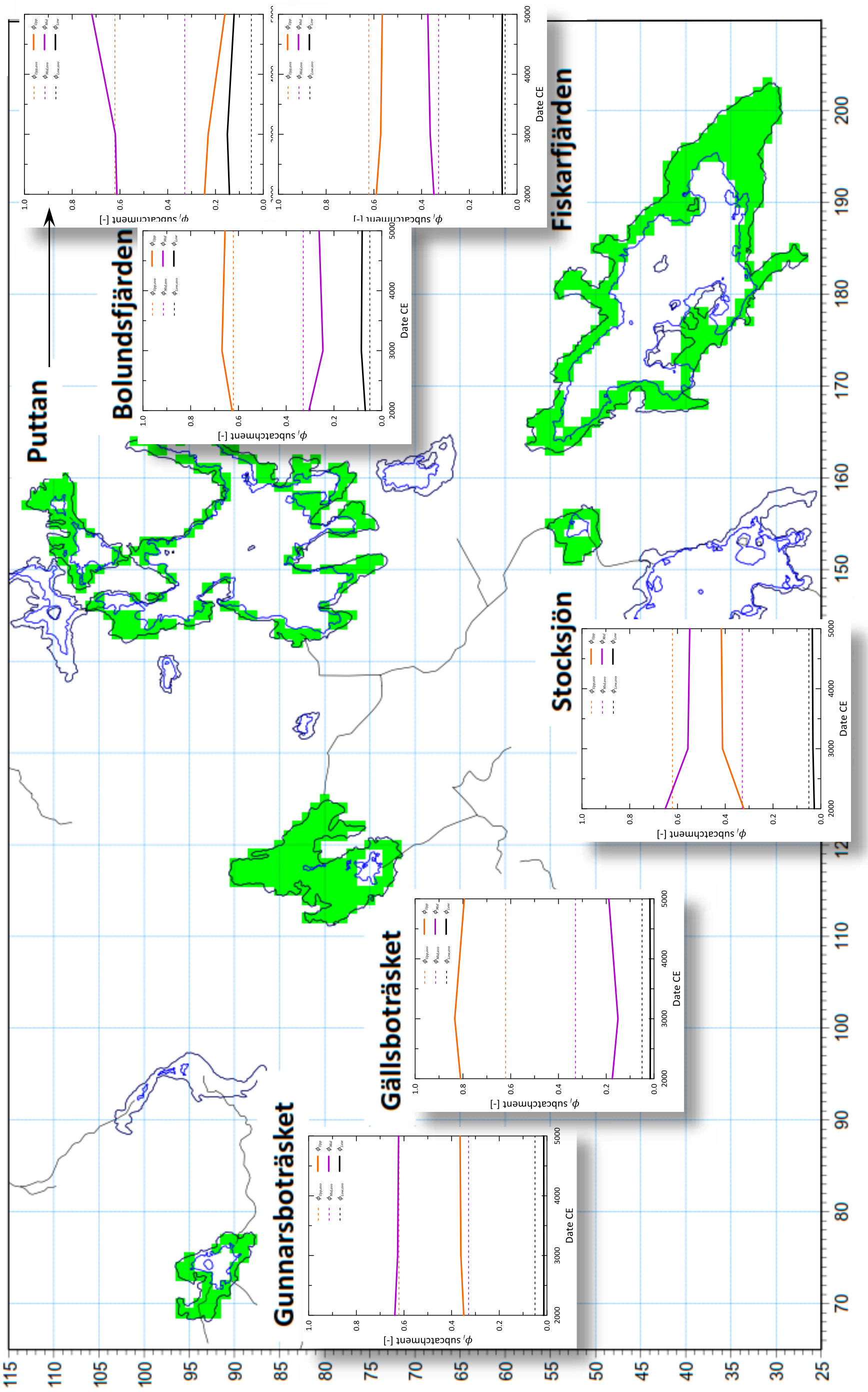


Figure 5: Division of the captured inflow to the regolith layers of the six lakes as a function of time., Results are compared to the "average object" (dashed lines). The fluxes are calculated using:

$$\phi_i = \frac{F_{subCatch,i}}{\sum\limits_{i=Low,Mid,Wat} F_{subCatch,i}}.$$

Most of the captured “runoff” flows into the upper regolith (~ 60 to 65%), with around 30 - 35% into the mid-regolith. Typically less than 5% flows into the lower regolith. This analysis therefore has implications for the implementation of GEMA-Site.

Figure 5 shows the plots of the changes in the partitioning of sub-surface flow for the six lakes at the three times. This puts the ϕ_i in their successionary context. Of the six, *Puttan* and *Bolundsfjärden* are nearest to the coast line and are just emerging – presumably undergoing the most rapid change. *Fiskarfjärden* is similarly close the coastline. *Bolundsfjärden* and *Fiskarfjärden* are the two largest lakes and have a similar distribution between water and terrestrial areas[1]. Their equivalent ϕ_i are similar to the “average object”, despite the temporal variation, with Bolundsfjärden having a slightly higher flows into the upper regolith.

For the other three lakes there is a marked difference however. For *Gunnarsboträsket*, *Puttan* and *Stocksjön* there is more flow into the mid regolith compared to the upper regolith. Clear trends are not readily identified. Nevertheless, it is clear that the average object is not a good representation of the six lakes and so is unlikely to be representative of anything useful in the landscape. The high relative flux in the upper regolith inflow of Gällsboträsket model may reflect the maturity of the lake/mire system there. a range of values for the ϕ_i is suggested by this analysis.

2.3. Discussion and summary

The aims of the RFI were to:

- better understand the basis for the “average object” used by Bosson *et al.* (2010) to provide water flux parameterisation to the radionuclide transport model (Avila *et al.*, 2010);
- use the water balance description for the six lakes at 2000, 3000 and 5000 CE to inform the evolution of the flow model in GEMA-Site.

The analysis in the previous section prompts comments in respect of:

- the transparency and reproducibility of elements of the SR-Site radionuclide transport model, namely the “average object”;
- the suitability of the “average object” approach as a way of populating the dataset for the landscape model of radionuclide transport;
- implications for alternate modelling

Transparency and reproducibility of the “average object”

Although the “average object” is quoted by Bosson *et al.* as being based on an average water fluxes in the basins of the six lakes existing in the present-day biosphere, estimated at 5000 CE by MIKE-SHE, it has not been possible to reproduce the numerical values used to express the generic hydrology and water balance of the basins by SKB (see Figure 1).

SKB provided most of the requested numerical data for the six lakes at the three times. The other request – for a detailed derivation of parameters in the TR-10-06 radionuclide transport model – has not been answered. Taken together the numerical

[1] “Large is relative” Though large in the context of the six lakes, the topography of the bed of *Öregrundsgrepen* to the northeast of the site suggests that there will be several lakes significantly larger than these two in the future.).

basis for the "average object" and the rationale behind the parameterisation of "average object" are therefore somewhat lacking in the model description and usage in SR-Site.

Confidence in the radionuclide transport model is therefore less than sufficient. Understanding of the potential radiological consequences arising from release to the future Forsmark landscape therefore requires application of the SSM-sponsored alternate model, GEMA-Site.

Suitability of the "average object" approach

As noted above, the focus on the *usage* of MIKE-SHE results in the dose assessment model meant that a detailed review of the MIKE-SHE modelling itself, particularly in respect of the evolving hydrology of the future Forsmark landscape, was not carried out at a sufficient level of detail. This means that the review of SR-Site is dependent on a numerical results (from MIKE-SHE) that have not been subject to the same scrutiny as the dose assessment model. This is understandable, the aim of the review was to determine the adequacy of the assessment of potential radiological impacts. A better understanding of the workings of, and results from, the MIKE-SHE model would have helped the reviewers to form a clearer picture of the *potential* for alternate interpretations of the evolution of the flow system in the regolith over the period of the assessment. It is likely that there is more that could be done to link the evolving flux maps for the landscape objects (ie, the basins) directly to the landscape model. Certainly a single non-evolving flux map is insufficient, the three time points of 2000, 3000 and 5000 CE are too few and the six lakes are not representative of the morphology of lakes anticipated from the topographic maps of the bed of the *Öregrundsgrepen* to the northeast of the planned repository location: there will be significantly larger lakes that will form over the next ten kyear.

The "average object" approach is very-much a snapshot of average conditions in six widely different lakes at different stages of maturity. The question is: would alternate flow systems (with evolutionary sequences) significantly change the values of the Landscape Dose Factors (LDFs) calculated by SKB as there surrogate for radiological impact? This is, in part, addressed by the sensitivity analysis carried out using GEMA-Site in the Chapters 3 and 4 below.

Implications for alternate modelling

Much of the analysis in section 2.2 is carried out to produce practical details for inclusion in the GEMA-Site modelling below. In requesting details of the flow systems for the six lakes at 2000, 3000 and 5000 CE it was hoped that the evolution of each of the lakes would be discernible so that an improved understanding of the flow system in GEMA-Site could be implemented.

Figure 3 shows that for four of the lakes there is little change in the areas of the terrestrial and aquatic system in the 3 kyear between 2000 and 5000 CE. Access to (and understanding of) the MIKE-SHE results (or similar) for the evolving flow systems in the landscape would be required to adequately characterise the evolutionary nature of the basins in the landscape. Consequently the hydrology in the GEMA-Site must remain restricted to the first approximation described by Kłos (2015).

There are some practical details that emerge from the analysis. Primarily, the interaction of the sub-catchment (SKB terminology) = Outer basin (GEMA-Site) is useful since it implies the range of values that might be expected for the distribution of vertical and sub-horizontal flows in basins.

3. Overview of the GEMA-Site model

3.1. Key features

Kłos (2015) gives a complete description of the basis for the model taking into account evolution in the system caused by landrise with an interpretation of the evolution of the flow system in the basin as different areas of the basin emerge from the sea during the modelled period with the consequence that hydrologic inputs to the system interact with different parts of the system at different times.

Figure 6 shows a simple interpretation of the evolving flow system for a basin modelled as three modules: Outer, Inner and Central. Transitions are treated as step changes related to land rise and sedimentation the lake phase and continued organic deposition in the wetland phase. Note that the *wetland phase* (Figure 6d) is the hydrologic configuration that most closely matches the situation as modelled in the SR-Site "average object" and thereby the SR-Site radionuclide transport model.

Appendix 3 provides further detail concerning the configuration of the model, including the numerical values for the water fluxes in the Reference Case model described by Kłos (2015). This illustrates how the flow system changes according to the transition times for each module:

- t_{sea} – transition from sea to bay (when the water column in the module no longer exchanges parcels of water with the rest of the Öregrundsgrepen)
- t_{aqu} – end of the aquatic period (no standing water in the module: water compartment disconnected and inventory redistributed).

For each of the modules, these times are given by

$$t_{sea} = \left| \frac{l_0 - l_{bay}}{\dot{l}_{uplift} - \left(M_{tpi} - M_{tpo} \right) \big/ A_{obj} \rho_{gl}} \right|$$

$$t_{aqu} = t_{sea} + \left| \frac{l_{bay}}{\dot{l}_{uplift} - \left(M_{tpi} - M_{tpo} \right) \big/ A_{obj} \rho_{peat}} \right|$$

Which includes the initial depth of the module below the Baltic (l_0 m) the depth of the water column on transition to bay conditions (l_{bay} m). The main driver for this transition is the land uplift rate ($\dot{l}_{uplift}$ m year^{-1}). Sedimentation also plays a role, depending on the net sedimentation rate as the balance between the mass input at the *top* of the compartment (sedimentation M_{tpi} kg year^{-1}) and the output (resuspension, M_{tpo}). During sea and lake stages the composition of the deposited material changes as reflected in the density parameters for sea and lake (glacial/post-glacial clay and peat respectively).

Transition to agriculture occurs at a time chosen by the human population. In the reference model the time of transition is t_{agri} = 19000 years after the start of the simulation. Only the Central basin is assumed to be converted to agriculture. This is the receiving compartment for the release and where the highest concentrations are likely to arise. There are accumulations in other parts of the basin but these are much lower than in the Central basin (Kłos & Wörman, 2015).

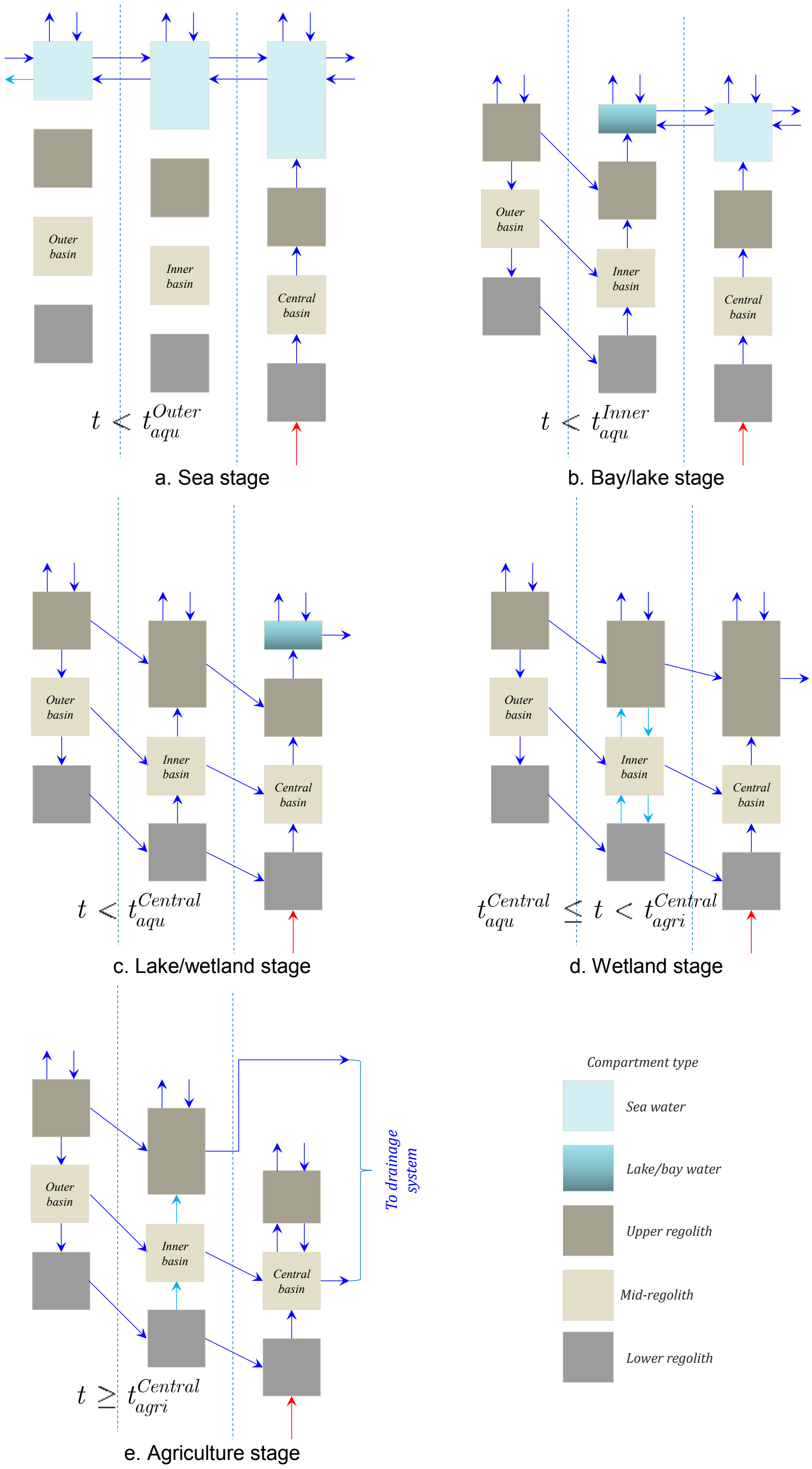


Figure 6: Evolution of hydrology during land uplift. Outer, inner and central basins are shown from left to right. With uplift and sedimentation the water level drops in each module. Release is to the lowest part of the basin with a small upward flux at all times. As water levels fall, flow from the outer, then inner basin is directed sub-horizontally towards the central basin contributing to increased upward fluxes. Change to agricultural conditions necessitates a modified and maintained drainage system. Radionuclide input is in groundwater in the bedrock to the lower regolith of the Central basin (red arrow).

Release of radionuclides to the basin is assumed to be to the lowest part of the topography and to be driven by topography-controlled gradients at the surface. For the flow system defined in the Reference Case, any dispersed release of groundwater to the Inner and Outer basins only acts to reduce the calculated doses. For this reason only the Central basin release is considered further.

The Reference Case dataset for the hydrological model is reproduced in Appendix 3 here. Variants and parameter distributions used in the probabilistic sensitivity analysis (psa) are discussed in Section 3.3 below.

From this data description, a clear difference between the GEMA-Site approach and the SR-Site transport model is seen. Water fluxes in SR-Site are defined by constant fractional parameters, linked to net infiltration according to evolving areas in the system. In GEMA-Site the flow system's fluxes change as different areas within the system become exposed as their water cover recedes. The fractional flows in the sub-horizontal domain are, again, linked to net infiltration in but the fractional are not constant. In one respect the SR-Site model better reflects the evolution of the lake/wetland system than the GEMA-Site model: the areas of terrestrial and aquatic ecosystems vary in time and the wetland grows while the lake shrinks. To obtain a similar feature in GEMA-Site would require a higher degree of lateral discretisation with more than the three modules included here. Nevertheless, the models give comparable results (Kłos, 2015) with increases confidence in the two modelling approaches.

In each model the fluxes in the modelled systems are linked directly to the inputs to the system and distinct ecosystem areas within the basin. The Reference Case parameters in the GEMA Site are listed in Table 1. Numerical values for the Reference Case model are listed in Table 2. Water fluxes are written in terms of the input parameters, for example, the water fluxes out from the top and bottom faces of the Outer basin's upper regolith compartment ($F_{upp,dno}^{Outer}$ and $F_{upp,bto}^{Outer}$ m^3 year^{-1}) are

$$
\begin{aligned}
F_{upp,dno}^{Outer} &= \phi_{upp}^{Outer}\left(P-E\right)A_{obj} \\
F_{upp,bto}^{Outer} &= \left(1-\phi_{upp}^{Outer}\right)\left(P-E\right)A_{obj}
\end{aligned},
$$

Table 1. Parameters governing water fluxes in GEMA-Site. Reference Case taken from Kłos (2015).

Parameter		Value	Module	Description
P	m year^{-1}	0.56	all basins	Precipitation (Lindborg, 2010)
E	m year^{-1}	0.4	all basins	Evapotranspiration (Lindborg, 2010)
v_{geo}	m year^{-1}	0.01	Central basin	Bedrock adv. velocity sea stage (Bosson *et al.*, 2010)
τ_{wat}	year^{-1}	0.017	all basins	Residence time of water parcels in grepen (Aquilonius, 2010)
i_{uplift}	m year^{-1}	-0.006	all basins	Isostatic uplift rate, interpreted from SKB (2010)

Table 2: Numerical values for the GEMA-Site Reference Case model (Kłos, 2015).

Parameter	Units	Value	Scope	Comments
A_0	m^2	10^5	Central Basin	Initial object area
l_{bay}	m	5	Central Basin	Depth on isolation from sea
t_{colony}	year	100	Central Basin	Time for terrestrial colonisation
t_{agri}	year	19000	Central Basin	Time of conversion to agriculture
l_{min}	m	0.01	lower regolith	Minimum allowed thickness
l_0	m	1	lower regolith	Initial thickness
l_{min}	m	0.01	mid regolith	Minimum allowed thickness
l_0	m	0.9	mid regolith	Initial thickness
l_{min}	m	0.01	upper regolith	Minimum allowed thickness
l_0	m	0.1	upper regolith	Initial thickness
$l_{agri,root}$	m	0.3	upper regolith	Agricultural rooting zone
l_{min}	m	0.2	water	Depth at end of aquatic state
l_0	m	80	water	Initial water depth
A_0	m^2	10^6	Inner Basin	Initial object area
l_{bay}	m	5	Inner Basin	Depth on isolation from sea
t_{colony}	year	100	Inner Basin	Time for terrestrial colonisation
t_{agri}	year	25000	Inner Basin	Time of conversion to agriculture
l_{min}	m	0.01	lower regolith	Minimum allowed thickness
l_0	m	1	lower regolith	Initial thickness
l_{min}	m	0.01	mid regolith	Minimum allowed thickness
l_0	m	0.9	mid regolith	Initial thickness
l_{min}	m	0.01	upper regolith	Minimum allowed thickness
l_0	m	0.1	upper regolith	Initial thickness
$l_{agri,root}$	m	0.3	upper regolith	Agricultural rooting zone
l_{min}	m	0.2	water	Depth at end of aquatic state
l_0	m	75	water	Initial water depth
A_0	m^2	10^7	Outer Basin	Initial object area
l_{bay}	m	5	Outer Basin	Depth on isolation from sea
t_{colony}	year	100	Central Basin	Time for terrestrial colonisation
t_{agri}	year	25000	Outer Basin	Time of conversion to agriculture
l_{min}	m	0.01	lower regolith	Minimum allowed thickness
l_0	m	1	lower regolith	Initial thickness
l_{min}	m	0.01	mid regolith	Minimum allowed thickness
l_0	m	0.9	mid regolith	Initial thickness
l_{min}	m	0.01	upper regolith	Minimum allowed thickness
l_0	m	0.1	upper regolith	Initial thickness
$l_{agri,root}$	m	0.3	upper regolith	Agricultural rooting zone
l_{min}	m	0.2	water	Depth at end of aquatic state
l_0	m	70	water	Initial water depth

where the area of the module is A_{obj} m^2 and precipitation and evapotranspiration are P and E respectively. The distribution of the flux between lateral and vertical flow is ϕ_{upp}^{Outer} (see Section 2.2). Similar relations hold for the mid and lower regolith compartments. Appendix 3 lists all such expressions, taken from the Ecolego implementation of the model, including the timing parameters used to switch the state of the flow system.

The radionuclides considered are those from the original modelling (Kłos *et al.*, 2014a); the release is 1 Bq year^{-1} of ^{79}Se, ^{94}Nb, ^{129}I and ^{226}Ra (for which the daughters ^{210}Pb and ^{210}Po grow in). These are significant radionuclides in the SR-Site assessment. Both ^{129}I and ^{226}Ra have high LDFs and the highest early releases (SKB, 2011).

A range of exposure pathways are considered in the model. These include consumption of marine and freshwater organisms, natural foodstuffs during the wetland (natural ecosystem) period as well as a comprehensive range of agricultural pathways. These pathways are switched in and out of the model according to the state of the ecosystem in the modules at different times. Also calculated are inhalation and external exposure doses arising from accumulation in the upper regolith and according to different patterns of human behaviour in the different ecosystems.

Since the initial modelling the use of local freshwater resources has been included for all terrestrial stages. When freshwater lakes exist these can be used for water consumption by humans and livestock. During the wetland period alternative (non-contaminated) water bodies are assumed. During the agricultural phase there are three water usage scenarios:

- Water from the surface drainage system (see Figure 6e);
- Water from a shallow well in the lower regolith of the Central Basin;
- Irrigation, where crops are irrigated from the well water (drainage system water could be used but leads to lower doses).

As the RFI response was not able to give additional detail as to the evolution of the flow field in the basin it was decided that this initial formulation of the evolving flow system would be used to investigate the range of dose-response and at the same time to assess the parameters in the model description that have the most influence on dose.

3.2. GEMA-Site for probabilistic sensitivity analyses

Since the initial modelling with GEMA-Site (Kłos *et al.*, 2014a) the model has been reviewed and updated (Kłos, 2015). Deterministic results have been presented to the 2015 IHLRMWC (Kłos & Wörman, 2015; Kłos *et al.*, 2015). The version of the model used here is GEMA-Site 1.3c.

The parameters sampled fall into two categories, those that affect radionuclide accumulation and uptake – the regolith k_ds and concentration ratios in foodstuffs; and those that affect water fluxes directly (and so the flow system). The former are taken from the database of the SR-Site radionuclide transport model (Nordén *et al.*, 2010). The latter – the areas of modules within the basin and so forth are based on the analysis of characteristics discussed by Kłos (2015).The values used here are listed in Appendix 3.

The assumed areas of the three module in this lateral discretisation of the basin are known to have an important influence om the dose arising from the release (Kłos *et al.*, 2015). Figure 7 gives an illustration of how results can vary with different assumptions. The plots compare the reference case model (the "7-6-5 geometry" with outer, inner and central basins having areas 10^7, 10^6 10^5 m^2 respectively) and a variant with "5-4-4 geometry" (10^5:10^4:10^4 m^2). The former has conversion at the reference value of 19000 years from the start of the release and the second has the imposition of the managed drainage system at the end of the lake period of the central basin at year 13148. Well water is the source of domestic and agricultural water supplies. Further analysis is discussed in Chapter 5 below.

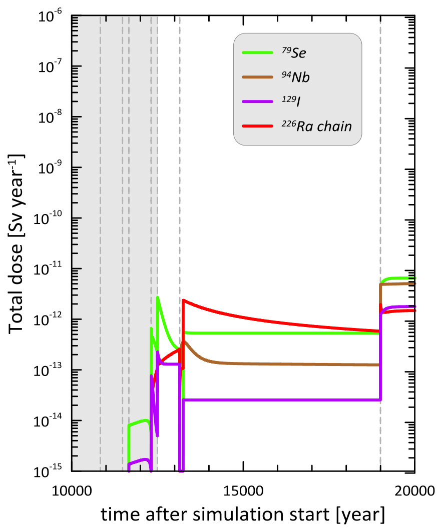
Combined with the analysis of basin areas in the future Forsmark landscape (Kłos, 2015) these results this justifies the set of pdfs assumed for module sizes in the probabilistic analysis here:

- Central basis: uniform, with bounds (5×10^3, 10^5) m^2,
- Inner basin: uniform, (10^3, 10^6) m^2
- Outer basin: uniform (10^4, 10^7) m^2.

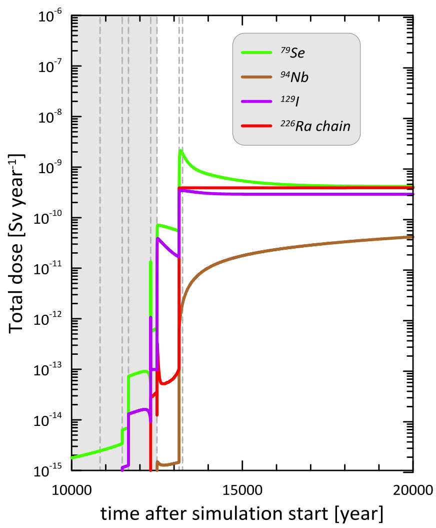
As this is a sensitivity analysis rather than a full probabilistic dose assessment, no correlations are assumed so that it is possible to have small outer and inner basins combined with a large central basin.

In addition to the nuclide specific parameters noted above, the effect of soil characteristics has also been included. Soil particulate densities (corrected from SKB's quoted bulk densities; Löfgren, 2010; Aquilonius, 2010) are also sampled as are the soil/sediment porosities in the same source. The time of conversion to agriculture is also sampled in the range 11200 to 20000 years.

Most sampled parameters can be implemented directly. The deterministic version requires some modification to allow the parameters and processes investigated in the



(a) Reference basin ("7-6-5 geometry"), t_{agri} = 19000 year



(b) Small basin ("5-4-4 geometry"), t_{agri} = 13148 year (conversion as soon as possible)

Figure 7. Illustration of doses alternative assumptions regarding basin size and time of conversion to agriculture – variants on the reference case values. Water from shallow well. Further discussion is found in Chapter 5 of this report.

probabilistic sensitivity analysis to be adequately represented. Interdependencies in the model require the following parameters to be introduced:

- Water fluxes in the Outer basin. The parameters ϕ_{upp}^{Outer} and ϕ_{mid}^{Outer} partition the infiltrating water flux at the top of the upper regolith at times after the aquatic period. The factors determine the lateral and vertical fluxes from the upper and mid regolith compartments respectively. The proportions are $\left(1-\phi_i^j\right)$ flows laterally and ϕ_i^j vertically. It is not practical to sample both the upper and mid-regolith fractions, instead they are assumed to be related by the sampled parameter f_ϕ^{mid}, so that $\phi_{mid}^{Outer} = \left(1-f_\phi^{mid}\right)\phi_{upp}^{Outer}$.
- A factor describing the volumetric moisture content of agricultural soils. Porosity of the compartments is included in the psa. Because of the proximity of the water table to the surface it is assumed that all but agricultural soils are saturated. Sampling both the porosity and volumetric moisture content of the agricultural upper soil without correlation could lead to unphysical results. As a simple expedient it is therefore assumed that the volumetric moisture content is given by $\theta_{agri} = p_\theta \varepsilon_{agri}$, with the sampled parameter being p_θ.
- Time of the imposition of agriculture in the Central basin. The basic resolution of the dose assessment model is 1 year. The time of transition from natural drainage to managed agriculture drainage is sampled. However, the sampled parameter is a real, rather than integer number. for this reason the sampled parameter is p_{agri} and this is converted to an integer number to give the date of transition: $t_{agri} = \mathrm{int}\left(p_{agri}\right)$.

4. Probabilistic Sensitivity Analysis results

4.1. Implementation

With the model outlined in the preceding chapter three sets of calculations have been run using the Ecolego modelling framework. Each of the three assumptions for local water usage (drainage system, well, well with irrigation) are evaluated. The model is run in probabilistic mode with 1000 Latin Hypercube Samples with no correlations.

The output quantity calculated is the annual individual dose arising from the release of the four radionuclides, ^{79}Se, ^{94}Nb, ^{129}I and ^{226}Ra (contribution of daughters growing-in in the biosphere included). Doses are calculated for each of the years from 10000 to 20000 after the simulation begins. Before this time, because of the choice of the initial depth of the sea, all basins remain covered by the Baltic and doses from the marine ecosystem are low.

The peak dose is evaluated for each radionuclide in the release. This differs from the 50 year average dose calculated by SKB in their generation of the LDF values (ie, lifetime averaged dose)[2]. Figure 7 suggest that agricultural doses are likely to dominate the results and that annual doses can remain reasonably constant over 50 years or so. Use of the peak annual individual dose simplifies the analysis here. The factors that influence peak dose are also those that influence the 50-year average dose.

Ecolego allows sensitivity analysis to be performed. The Spearman rank correlation coefficient is used to determine sensitivity. Scatter plots of key parameters are also used to illustrate trends.

4.2. Analysis

4.2.1. Rank Correlation Coefficients (RCC)

Table 3 lists the results for the three water usage scenarios for each of the four radionuclides released to the base of the Central Basin lower regolith. Only those results for which the absolute value of the RCC ≥ 0.1 are shown. Below this value the correlation is too low to be meaningful.

Looking at Table 3 the factors that influence dose can be classified as

- Sorption characteristics
  - strongly and weakly nuclide behave differently – ^{79}Se and ^{129}I cf. ^{94}Nb and the members of the ^{226}Ra chain

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[2] The fifty year average dose, $\langle D_{50}(t) \rangle = \frac{1}{50}\int_t^{t+50} D_{tot}(t')\,dt'$, is allowed by the SSM (2008) guidance. If there are any short term transients with high peak annual doses during the period, this quantity smooths them out to give a representative annual dose over the adult lifetime of the exposed individual.

Table 3: Results of the sensitivity analysis for the three water usage cases (|RCC| ≥ 0.1).

^{79}Se	RCC	^{129}I	RCC
OuterBasin.A_obj	-0.58	kd_organic (^{129}I)	0.65
kd_organic (^{79}Se)	0.45	OuterBasin.A_obj	-0.33
CR_fish_fw (^{79}Se)	0.25	CR_root (^{129}I)	0.18
CentralBasin.t_agri	-0.20	TF_milk (^{129}I)	0.15
kd_inorganic (^{79}Se)	0.19	CR_pasture (^{129}I)	0.13
CR_cereal (^{79}Se)	0.18	kd_inorganic (^{129}I)	0.12
CR_root (^{79}Se)	0.12	CR_cereal(^{129}I)	0.11
		CentralBasin.t_agri	-0.11
^{94}Nb	**RCC**	**^{226}Ra chain**	**RCC**
kd_organic (^{94}Nb)	0.68	CentralBasin.A_obj	-0.51
OuterBasin.A_obj	-0.26	OuterBasin.A_obj	0.42
kd_inorganic (^{94}Nb)	-0.14	kd_inorganic (^{210}Pb)	-0.28
CentralBasin.t_agri	-0.11	kd_inorganic (^{210}Po)	-0.28
CentralBasin.A_ob0	-0.08	kd_organic (^{210}Po)	-0.20
		kd_inorganic (^{226}Ra)	-0.18
		CR_game (^{210}Po)	0.10
		OuterBasin.phi_upp	-0.10

(a) drainage system

^{79}Se	RCC	^{129}I	RCC
OuterBasin.A_obj	-0.54	kd_organic (^{129}I)	0.69
kd_organic (^{79}Se)	0.47	OuterBasin.A_obj	-0.44
CR_fish_fw (^{79}Se)	0.28	CR_root (^{129}I)	0.16
CentralBasin.t_agri	-0.20	CR_cereal (^{129}I)	0.16
CR_cereal (^{79}Se)	0.19	CentralBasin.t_agri	-0.13
kd_inorganic (^{79}Se)	0.14	TF_milk (^{129}I)	0.12
		CR_pasture (^{129}I)	0.12
^{94}Nb	**RCC**	**^{226}Ra chain**	**RCC**
kd_organic (^{94}Nb)	0.67	CentralBasin.A_obj	-0.52
OuterBasin.A_obj	-0.28	kd_inorganic (^{210}Po)	-0.51
kd_inorganic (^{94}Nb)	-0.17	kd_organic (^{210}Po)	-0.25
		kd_inorganic (^{210}Pb)	-0.20
		OuterBasin.A_obj	0.19
		kd_organic (^{226}Ra)	0.14
		kd_inorganic (^{226}Ra)	-0.10
		CR_game (^{210}Po)	0.10

(b) well water

^{79}Se	RCC	^{129}I	RCC
OuterBasin.A_obj	-0.51	kd_organic (^{129}I)	0.64
kd_organic (^{79}Se)	0.47	OuterBasin.A_obj	-0.48
CR_cereal (^{79}Se)	0.25	CR_pasture (^{129}I)	0.17
kd_inorganic(^{79}Se)	0.21	CR_root (^{129}I)	0.16
CR_fish_fw (^{79}Se)	0.21	TF_milk (^{129}I)	0.14
CentralBasin.t_agri	-0.17	CR_cereal (^{129}I)	0.12
CentralBasin.A_obj	0.11	kd_inorganic(I-129)	0.11
^{94}Nb	**RCC**	**^{226}Ra chain**	**RCC**
kd_organic (^{94}Nb)	0.67	kd_inorganic(^{210}Po)	-0.75
OuterBasin.A_obj	-0.21	CentralBasin.A_obj	-0.37
kd_inorganic (^{94}Nb)	-0.17	kd_inorganic (^{210}Pb)	-0.14
CentralBasin.t_agri	-0.10	kd_organic (^{210}Po)	-0.12
		CR_game (^{210}Po)	0.10

(c) well water and irrigation

- the relative strength of sorption in the upper regolith (organic material) compared to the inorganic k_d (material in mid and lower regolith)
- Basin characteristics
  - The areas of the modules often rank highly and the size of the outer basin can have a greater influence than the size of the central basin (the place where the release, accumulation and exposure take place).
  - The time of transition to agriculture weakly influences of peak dose
- Concentration ratios and transfer factors
  - These also show a variance between strongly and weakly sorbing radionuclides. Where they have influence it principally seen thorough the agricultural pathways though the concentration of ^{79}Se in fish during the lake period is also indicated as a sensitive parameter.

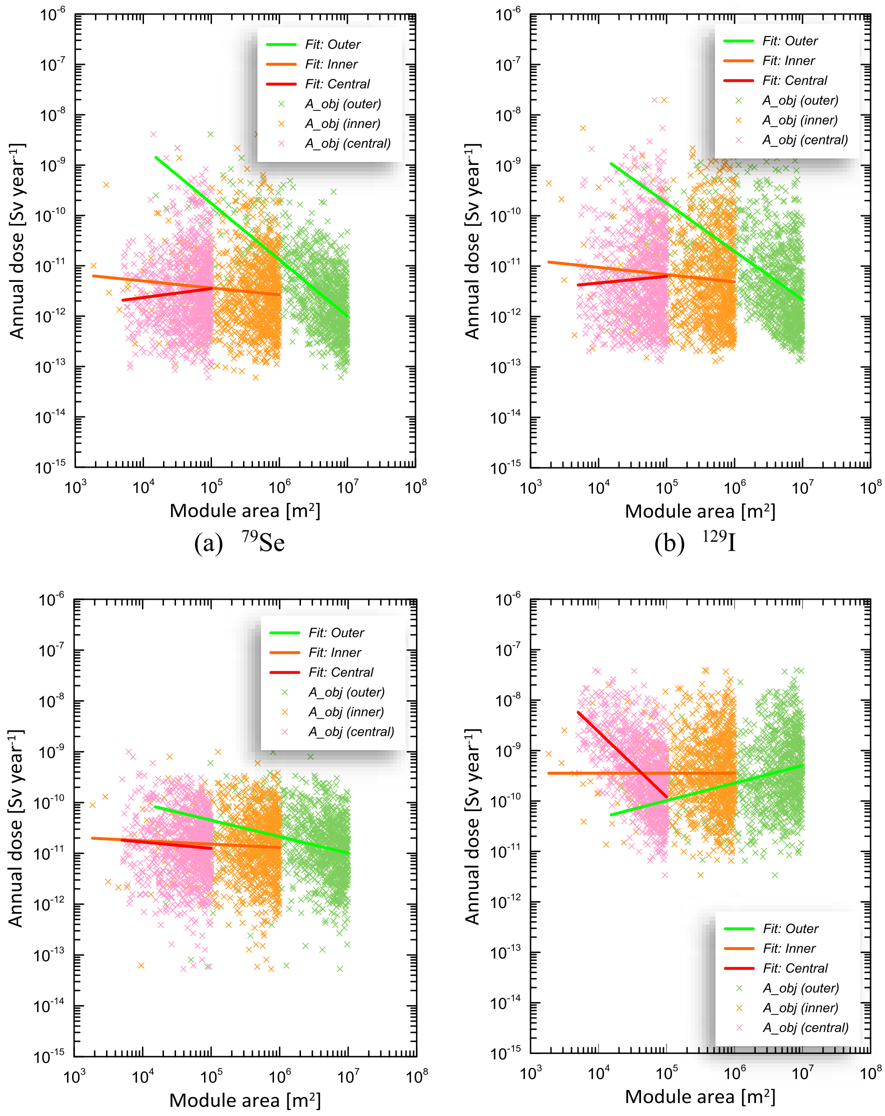
4.2.2. Interpretation of results

Basin geometry (areas of outer, inner and central basins) feature in the top two most influential parameters for each of the radionuclides and water use variants. The Inner basin has no significant influence and the Central Basin area has the expected negative correlation on account of spatial dilution in the area from which agricultural produce is derived. However, this is primarily for the ^{226}Ra chain, with a relatively low signal, for ^{94}Nb. These are both examples of the more strongly sorbing radionuclides.

For the weakly sorbing radionuclides (^{79}Se and ^{129}I here) it is the area of the **Outer basin** that has the strongest influence. The greater the collecting area for net infiltration in the basin as a whole, the lower the dose. The key factor here that of *throughput* of contaminated water. Because the k_ds are relatively low the high throughput rapidly washes contaminants from the system with little accumulation. This feature also affect dose from ^{94}Nb. Higher doses for ^{94}Nb arise for combinations of lower k_d in the lower and mid-regolith layers (negative correlation with inorganic k_d) and higher sorption in the organic layers (positive correlation). The importance of retention in the lower regolith for the low k_d nuclides is seen in the results that both ^{79}Se and ^{129}I have positive correlations of dose with inorganic k_d. This acts to counter the washing out of the radionuclides by the high throughflow, delaying loss for dose to arise from the upper regolith.

A related effect is seen for the ^{226}Ra chain. In this case, however, there is a strong positive correlation of doses with area of the Outer basin. There is a significant negative correlation between inorganic k_d and dose for each of the radionuclides in the chain. In the modelling of the chain there are opposite influences from the k_ds of ^{226}Ra and ^{210}Po. A positive correlation for the organic k_d of ^{226}Ra acts to retain ^{226}Ra in the upper regolith where is has longer to decay to ^{210}Po (via ^{210}Pb). Doses from the release of ^{226}Ra are dominated by daughters, particularly ^{210}Po. The role of the Outer basin's area in this case is to wash the highly sorbing ^{226}Ra (and ^{210}Pb) into the upper regolith where ingrowth of ^{210}Po is important.

Figure 8 shows scatter plots of dose vs. module size for the released radionuclides in the case of well water usage. These plots support the results from the RCCs. Trends in the data are illustrated using a fitted power-law for each of the scatter plots. The strongest signals come from the effect of the area of the Outer basin for lower k_d nuclides: the greater the throughflow the greater the dilution. There is a similar effect



(a) ^{79}Se (b) ^{129}I (c) ^{94}Nb (d) ^{226}Ra chain

Figure 8: Scatter plots indicating the influence of module areas on annual individual dose. Case with well water usage. Results for each module area are shown. Fitted lines are power-law fits to illustrate data trends. This is similar to the RCC but is less indicative.

for ^{94}Nb though the trend is less pronounced. For the ^{226}Ra chain the effect is reversed. The strongest influence on the ^{226}Ra chain is the spatial dilution effect of the Central basin's area. It is not believed that the slight positive relation for the Central basin area for ^{79}Se and ^{129}I is meaningful, although the slight negative slope of the results for ^{94}Nb is consistent with that from the ^{226}Ra chain. The RCC values corresponding to these results are below the 0.1 threshold. The influence of the area of the Inner basin is seen to be similar to that of the Outer basin, suggesting that the three module discretisation may not be necessary.

The time of conversion to agriculture shows a slight negative correlation with dose for all of the released radionuclides except ^{226}Ra. The effect is more pronounced for ^{79}Se. This is consistent with the effects of throughflow. In the case of earlier conversion there has been less time for the accumulated activity of the lower k_d radionuclides to be washed from the system. During the lake period there is residual net upward flux beneath the lake of the Central basin with relatively high accumulation in the growing organic material of the lake bed sediment. With the change to the flow vectors during the wetland (and agricultural) phase there is greater throughput in the upper regolith washing out accumulation of lower k_d nuclides. Broadly, the comparison between early and late conversion in Figure 7 illustrates the effect of time of agricultural conversion well.

The other parameters that feature on the RCC results are the concentration ratios and transfer factors. A possible consequence of the way in which the end-stage of the lake system's evolution is handled in the model is that ^{79}Se's CR for freshwater appears as an important determinant of dose. Conceivably this occurs at the latter stages when the volume of the lake is small. However, the geometric mean for this parameter is particularly high for ^{79}Se and this also contributes to the sensitivity indicated here. In the main the CR and TF values that are flagged in this analysis have relatively weak RCCs and they have most influence on the lower k_d nuclides.

In particular, the way in which concentrations in game animals is modelled is cause for some comment. The approach assumed here is taken from Avila *et al*. (2010). Game concentrations are scaled from the concentration in natural foodstuffs using the concentration factor CR-game and the concentration in natural foodstuffs is derived from the concentration in the upper regolith using a similar concentration ratio. Situations where the game pathway is indicated as important suggest that a better representation of FEPs for accumulation in game might be required.

Results for the surface drainage and well water scenarios are similar. This is because the well water is assumed to be taken from a shallow well in the lower regolith. In the agricultural system this water discharges through the emplaced drainage to surface water channels, augmented by captured and diverted water fluxes from the combined inner and outer basins. The drainage system has slightly lower concentration than the well water. Deep (bedrock) wells are not considered here since the concentrations therein are the province of geosphere modelling, not the biosphere.

The distribution of water fluxes in the Outer basin between vertical drainage and lateral and sub-horizontal flow (parameter *OuterBasin.phi_upp*) has only a minor influence in the case where water supplies are taken from the surface drainage system. This suggests that the model overall is not sensitive to the route taken to flows into the Central basin.

Well water abstraction combined with irrigation is therefore the maximum interaction with contaminated groundwater in the model as configured. Because the abstraction is from the lower regolith, with direct interception by the crops, accumulation in the upper regolith is less important[3]. The pattern of RCCs is slightly different to the other two water usage cases; for example, the timing of the agricultural transition is detected for ^{94}Nb and retention in the lower regolith of ^{210}Po is the most important determinant of the ^{226}Ra chain dose.

[3] Parameters controlling irrigation interception have not been sampled here since the purpose was to look at the effects of changes to the model of surface hydrology. The assumption is that there are five equal irrigation events during the year.

5. Synthesis - uncertainties in the SR-Site dose assessment modelling

5.1. Overall uncertainty

As well as investigating the parameters in the model that have the most influence on the calculated dose it is important to use GEMA-Site to investigate the potential magnitude and origins of uncertainty in the SR-Site dose assessment. The spread of results (5th to 95th percentile) obtained in the probabilistic sensitivity analysis discussed in the previous chapter can be compared to the reference modelling results and with selected deterministic results. SKB's LDF values themselves as well as results from the application of a "simple" modelling approach carried out by Walke (2014) also help describe the overall range of results. Figure 9 shows the LDF values and peak doses from the "simple" model in relation results from the modelling with GEMA-Site described here.

At first sight, the ranges shown in Figure 9 appear rather large. There is need to disaggregate the sources of uncertainty.

The first important point to note is that for the lower k_d species (^{79}Se and ^{129}I here) the estimates of LDF calculated by SKB in SR-Site *are* at the upper end of the range as calculated with the GEMA-Site alternate model. This suggests that the SR-Site

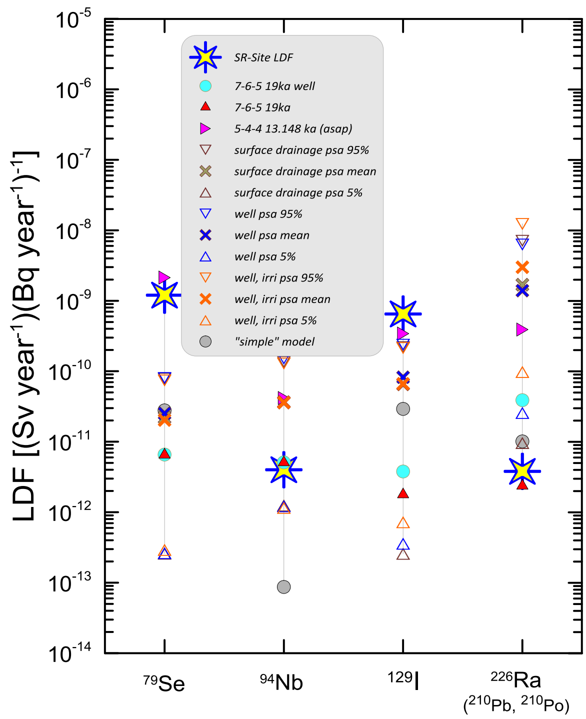


Figure 9: Comparison of SR-Site LDFs with ranges of values from the GEMA-Site psa. 5th and 95th percentiles and mean values are plotted for the three water use scenarios. Additionally to the SR-Site LDF values are plotted the peak doses for the 5-4-4 and 7-6-5 geometry results (surface drainage) from Figure 7 as well as the 7-6-5 geometry results for the well scenario. Walke (2014) has applied "simple" models to the SR-Site system description. These results are also indicated.

LDFs for lower k_d radionuclides are robust, as a consequence of the many pessimistic assumptions deployed by Avila *et al*.

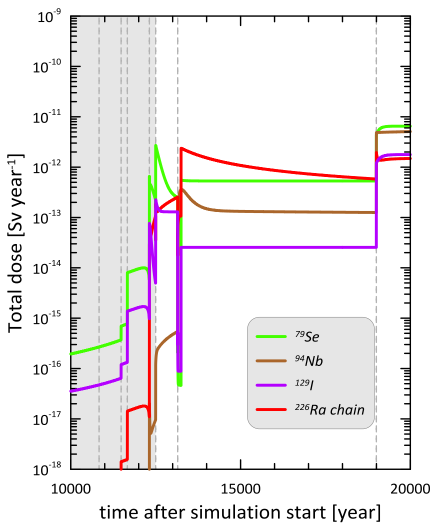
For the higher k_d species, ^{94}Nb and members of the ^{226}Ra chain, there is an indication that the SR-Site approach could underestimate the radiological impact of releases by some orders of magnitude. The following section addresses the sources of uncertainty expressed in Figure 9, looking at different features of the GEMA-Site model.

As an expression of the overall variability two measures are used – the maximum annual dose over the whole of the simulation period (from 0 to 20 kyear) and the dose immediately after the transition. In this way the maximum values include doses that might arise from non-agricultural ecosystems. Taking the dose just after the transition to agriculture allows the impact of any initial transients in the dose evolution caused by accumulations of radionuclides in the precursor ecosystem to be gauged. Figure 10 illustrates the procedure using a comparison of the evolution of doses in the reference basin assuming the transitions at 19 kyear and as soon as possible after end of the aquatic period.

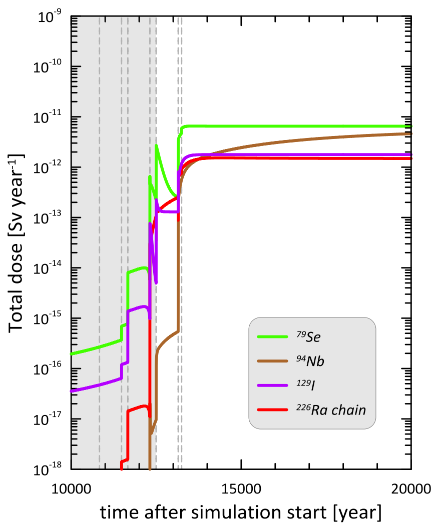
5.2. Sources of uncertainty

5.2.1. Transition to agriculture

The issue here is the extent to which longer term accumulations in the regolith can give rise to higher doses in agricultural systems. Comparing results from the reference basin using surface water resources and transition at 19 kyear with the "as soon



(a) reference case (t_{agri} = 19 kyear)



(b) t_{agri} = 13.148 kyear, "as soon as possible", after the end of the lake stage of the Central basin

Figure 10: Evolution of doses using the reference basin model – influence of time of transition to agriculture (t_{agri}) on dose. Default case with transition to agriculture at 19 kyear compared to the case with transition "as soon as possible" (at the end of the lake stage of the Central basin). Dashed lines indicate transitions to the flow system, shaded area denotes transitions for Outer and Inner basin ecosystems.

as possible" variant, with $t_{agri} = t_{aqu}$ = 13148 year shows that the highest doses come from the agricultural ecosystem in the case of ^{79}Se, ^{94}Nb and ^{129}I. For the ^{226}Ra chain, however, the peak dose comes from game consumption in the wetland phase. Accumulations of ^{210}Po are washed out of the wetland's upper regolith because, during this stage, lateral drainage of the wetland is active (Figure 6c → Figure 6d). There is a small peak just after the transition as the soil is drained and compacted for agriculture. For the other radionuclides, however, the flow system depicted in Figure 6e results in a slight increase over time with the maximum being reached sometime after the transition[4].

With the transition to agricultural land as-soon-as-possible the evolution shows a similar sudden increase following the start of agriculture. Each of ^{129}I and the ^{226}Ra chain show a slow increase upto the equilibrium values. This takes on the order of 500 years. For ^{94}Nb (with relatively high k_ds in each of the three regolith layers) the time to equilibrium is significantly longer, more than 7 kyear. ^{79}Se shows equilibrium almost instantaneously – in the first few hundred years post transition there is an insignificantly higher maximum.

These dynamics are of interest as it is uncertain whether agricultural land in a specific location will persist for longer than a few hundred years (Jansson *et al*., 2006). Doses in the immediate aftermath of transition are therefore a more reasonable expression of likely radiological impact. Figure 11 plots the maximum dose during the simulation and the maximum post transition values for a range of times of transition.

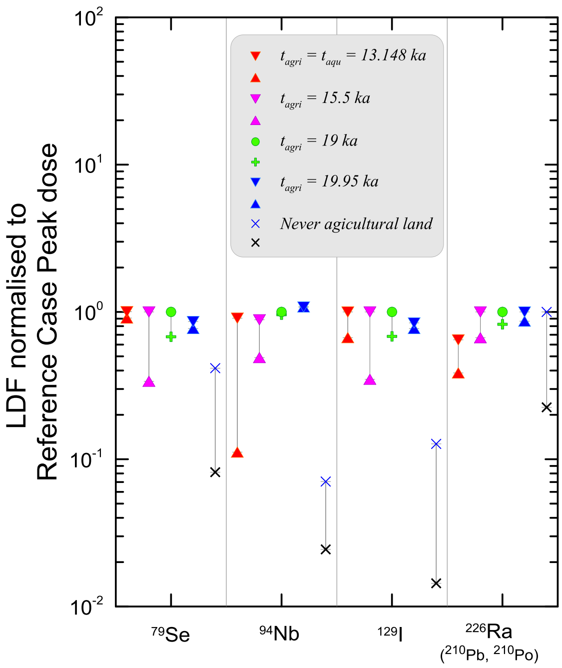


Figure 11: Deterministic sensitivity results for different times of transition to agriculture in using the 7-6-5 reference case basin model. Results normalised to reference case.

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[4] This contrasts with the SR-Site model of agricultural land where only washout is represented. Consequently the dose in the year following conversion to farmland is always the highest and this decreases in time. SKB use the 50-year averaged dose to calculate the LDF to account for this transient. Overall the effect is small – much less than a factor of two in the GEMA-Site reference basin.

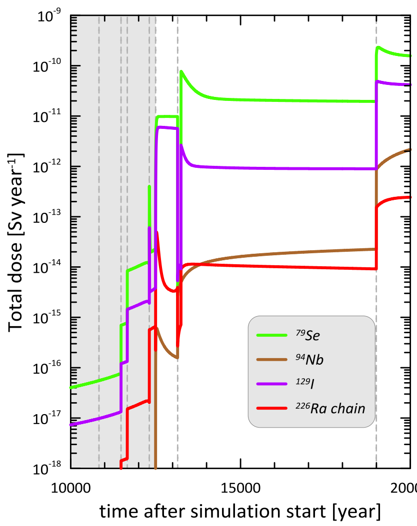
These results suggest that the timing of the transition is has little impact on the radiological impact. The maximum dose is similar in each case. Only the “never agricultural land” results are lower, emphasising the significance of agricultural ecosystems in dose assessment. The exception is the dose for the ^{226}Ra chain, as discussed, where natural ecosystems can give rise to the peak dose.

Because the dose immediately after transition is a better indicator of dose from agricultural systems the lower bound here is of interest. The role of accumulation is apparent. For ^{79}Se there is significant accumulation in the lake bed upper regolith and while this is rapidly washed out with the altered regolith flow system during the wetland phase there is a tendency for *re*-accumulation in wetland upper regolith. this is seen in the increase of the minima of the plots in Figure 11 with increasing t_{agri}. This accumulating trend is seen for the other three radionuclides in the release.

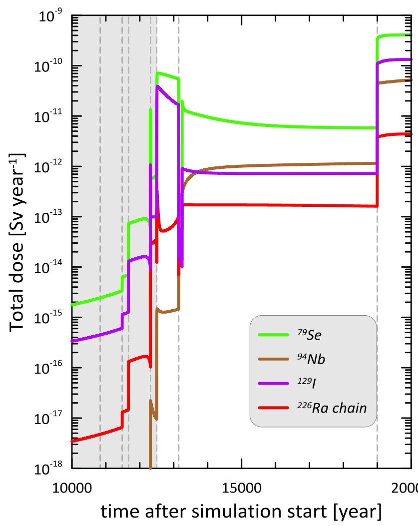
Overall the lack of sensitivity to time of transition to agriculture in these results is a consequence of the model. There are no situations where earlier transition gives rise to higher doses than the long term equilibrium dose values. The 19 kyear transition is a useful indicator of what the “landscape dose factor” should be. SKB’s approach, which estimated doses from agricultural systems at all times when land surface was available, with the LDF being taken as the maximum of this set of doses, produces a reasonable estimate of the potential radiological impact.

5.2.2. Basin geometry

Figure 10a shows the results for the reference basin. Figure 12 illustrates the differences in the evolution of dose caused by alternate basin geometries. The 7-6-5 reference case has areas in the ratio 10^7:10^6:10^5 m^2 for the outer, inner and central basins,



(a) “equal modules” case – the 5-5-5 geometry



(b) “small basin, small agriculture” case – the 5-4-4 geometry

Figure 12: Evolution of doses using the reference basin model – influence of basin geometry on dose. Two alternatives illustrate the influence of variant basin sizes on the evolution of dose, a small basin with equal areas and a smaller basin with smaller agricultural area compared to the Reference case in Figure 10a. The shaded area denotes transitions of Outer and Inner basin ecosystems.

respectively. The variants shown here are the 5-5-5 case, a relatively small total basin with the same agricultural area as the reference; the second variant is smaller basin with the inner and central basins each 10^4 m^2 (the 5-4-4 geometry). In this variation the time of transition to agriculture is maintained at 19 kyear.

Because the areas of the basins differ – the collecting area for net infiltration – these variants lead to systems with different hydrological characteristic. Doses during the transition from marine to terrestrial ecosystems vary considerably and doses at times before the formation of the lake in the central basins are notably different in each case. This makes a discussion of the details rather complex . For the purposes of understanding the potential influence of the evolving landscape on landscape dose factors, the range from maximum dose during the simulation and the dose immediately after the transition to agriculture are again used. A brief discussion follows with more detail provided by Kłos (2015).

Releases to basins with different sizes show differences not only in magnitude of dose but also in terms of dynamics. The ^{226}Ra chain in Figure 12 illustrate this. Changes to the ecosystem of the central basin on the isolation of the lake (at the transition denoted by the grey shaded area) lead to relatively high concentration in lake water. In the 5-5-5 case this decreases slowly whereas the decay is much more rapid in the 5-4-4 case. Similarly, post the agriculture transition, the rate of increase of dose towards the equilibrium value is different for the two alternative flow system representations. These features are a result of the differences in the regolith groundwater flow field embodied in the definition of the model. The dynamics of the ^{79}Se dose also provide instructive examples on the influence of the flow system model.

In these two smaller basin models (compared to the reference 7-6-5 geometry) the ecosystem with the maximum dose also shows some variation. In the 7-6-5 case the wetland ecosystem has the highest ^{226}Ra chain dose in the period after its formation.

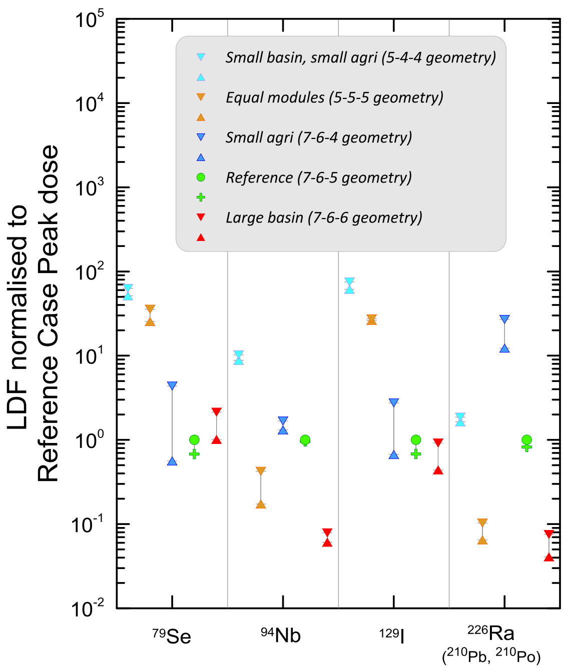


Figure 13: Deterministic sensitivity results for different times of transition to agriculture in using the 7-6-5 reference case basin model. results normalised to reference case.

In each of the 5-5-5 and 5-4-4 cases the agricultural ecosystem dominates. Figure 13 shows the range of values for five variant area models:

- small basin, with small agricultural area (5-4-4 geometry), small overall basin
- equal modules (5-5-5- geometry), small overall basin
- small agriculture (7-6-4 geometry), similar to the reference case with a smaller central area
- Reference case (7-6-5 geometry)
- Large basin (7-6-6 geometry), a simple case with a central area ten times larger than the reference.

These results support the results from the psa in Figure 8 for the variation of the module areas. Smaller basins with smaller overall water fluxes (simply expressed as the product of net infiltration and "collecting area" of the basin) give the highest doses. Here the 5-4-4 basin dominates for the less strongly sorbing ^{79}Se and ^{129}I as well as the more strongly sorbing ^{94}Nb. The effect of spatial dilution in the agricultural region is also seen. The 7-6-4 geometry gives the highest results for the ^{226}Ra chain. it is the *increased sub-horizontal water fluxes* in the larger basins that accounts for the increased dose. A similar signal is seen for ^{94}Nb but, in that case, 5-4-4 geometry gives the highest dose. A small agricultural area alone is not sufficient (as witnessed by the 7-6-4 geometry result).

5.2.3. Use of water resources

The preceding discussion accounts for significant parts of the uncertainty shown in Figure 9. A further important contribution to the variation comes from the assumptions about water resources exploited by the assumed population in the modelled basin.

As modelled in GEMA-Site there are two potential sources of freshwater for domestic and agricultural purpose. One is the accumulated drainage system water that represents the water that must be diverted from agricultural soils in order to keep them dry enough to cultivate. The other is and a shallow well in the lower regolith. One of the variants included in the ranges of Figure 9 is that the well water is also used to irrigate selected crops. During the lake phase, the water source was assumed to be the lake water but during this period there is no agriculture. At the end of the lake period, as the lake becomes clogged with sediment and vegetation and the wetland forms, it is no longer practical to use surface water.

These water use scenarios differ from the SR-Site assumption that drinking water was obtained from a well in the bedrock, the dilution characteristics of which are determined as a regional average figure (Avila *et al*., 2010). The assumed well capacity is relatively large and contributed to the relatively low drinking water doses in SR-Site (Walke, 2014). In SR-Site water usage from a well was always possible as lakes were assumed always to be present in the landscape. The evolving system implemented in GEMA-Site, with the lake evolving to wetland, would diminish the importance of this scenario. Rather than implement GEMA-Site with the assumed radionuclide concentration in bedrock-well water, a case with no contaminated drinking water has been implemented. In this assumption (which will give doses lower than in the case of the bedrock well) the local population obtain their water resources from uncontaminated sources, for example a lake in a nearby basin or from a public

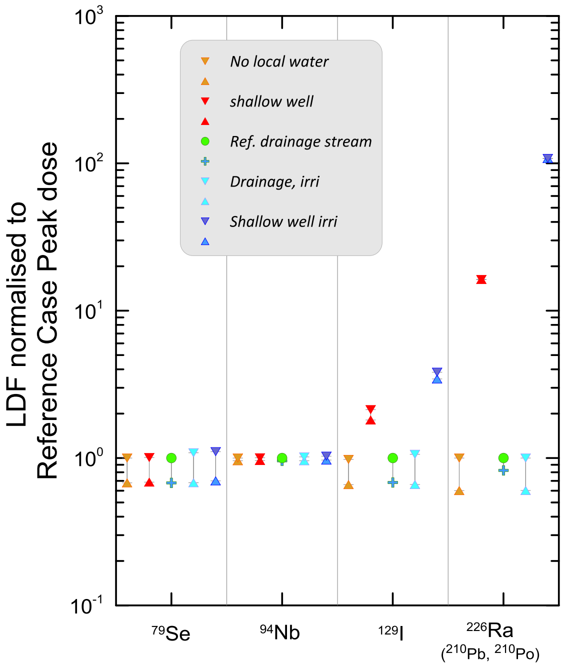


Figure 14: Deterministic sensitivity results for different assumptions about water resource exploitation. Reference case basin (7-6-5- geometry), agricultural transition at 19 kyear.

water supply sourced elsewhere in the landscape. Figure 14 shows an analysis of the impact of different patterns of water usage using the overall maximum and dose post agricultural transition method in the reference case 7-6-5- geometry basin with agricultural transition at 19 kyear.

These results emphasise the need to adequately characterise the habits of the potentially exposed population. For ^{79}Se and ^{94}Nb the assumptions for water usage make little difference, all results are closely clustered around the reference case result. For ^{129}I use of water from the shallow well has a more clearly defined effect, but increasing the dose only by a factor of around two or three if irrigation is included. For the ^{226}Ra chain, however, the results are more important. Because of the relatively high k_d of ^{226}Ra in the lower regolith there is significant accumulation and ingrowth of daughters can lead to over a factor of ten increase relative to the reference (drainage system water used for domestic and agricultural purposes) and no-well-water cases. If the well water is used for irrigation, doses can increase by around two orders of magnitude.

These factors therefore account for a good deal of the variation in Figure 9 and it should be born in mind that Figure 14 does not include the effects of variations in basin geometry discussed above.

5.3. Discussion

The alternate dose assessment model of the future Forsmark landscape carried out with GEMA-Site has been used to gauge the reliability of the LDFs published by

Avila *et al*. (2010). Differences in the results from the two models (SR-Site radionuclide transport model and GEMA-Site) are to be expected – they express alternative interpretations of the groundwater flow systems in the modelled basins. Similarly the "simple" modelling approach carried out by Walke (2014) contributes to the discussion. Figure 9 takes the results from SR-Site and Walke (2014) and places them in the context of the results from the probabilistic sensitivity analysis carried out using GEMA-Site and selected deterministic results from GEMA-Site.

How different are the three models? In essence they are very similar – they all employ the same vertical resolution adopted by Avila *et al*. They each, effectively, treat each basin in the landscape as distinct, recognising that the immediate area around the release point is the most important since most activity entering the biosphere system from the bedrock remains close to the release location. The same exposure pathways are considered in each case. The "complexity" of the SR-site modelling approach comes principally from the modelling of the entire landscape in which ecosystems change in time. The features, events and processes represented in the individual models are all relatively simple, straightforward and robust.

Where the models used here differ from the "standard" approach (eg, the Reference Biospheres Methodology developed by IAEA, 2003) is that the biosphere system evolves as a consequence of the climate change that brought about the end of the most recent glaciation. Two of the models – SR-Site and GEMA-site encode these changes directly into a coherent structure, resulting in switches that activate changes in the state of the model during the simulation. The "simple" approach uses a set of models that are run independently. The same judgement that the experienced modeller used to implement the "switches" in SR-Site and GEMA-Site are used outside the model execution to combine results in a consistent way. **It is not possible to use off-the-shelf biosphere models without major interpretation to match the specific conditions set by the site context.** Each of the models applied to the modelling of the future Forsmark landscape is conditioned by the site descriptive modelling that underlies the dose assessment.

Nevertheless, there are differences in the results and these come from two sources, one is the interpretation of the evolution of the site and the other comes from the assumptions regarding how the exposed population interacts with concentrations of radionuclides in the biosphere. The key feature that GEMA-Site includes is that the groundwater flow vectors change in time in relation to the elevation of the topographic surface in relation to sea level.

Two aspects of the GEMA-Site model have been investigated in some detail, time of transition to agriculture and the size of the basin and its internal organisation.

The time of transition to agriculture reflects how much time the radionuclide release from the bedrock flow system has to accumulate in agricultural soils prior to exposure. In terms of the radiological impact the dose are relatively insensitive to this parameter because it is the maximum dose over the simulation that dictates the dose conversion factor. While it is true that actual doses arising from earlier times would likely be lower than if longer accumulation were possible, this is because the persistence of agricultural land in any specific location is not certain to be more than a few hundred years. As modelled, doses from early conversion would approach the values predicted for later conversion if sufficient time as agricultural land were available for concentrations in agricultural land to reach steady state concentrations. As far as usage of LDFs in SR-Site is concerned, therefore, the suitable value would be taken from later conversion cases.

Basin geometry is a more complex issue. The SKB approach derived a representation of the average groundwater flow vectors from six basins at a single time point. This "snapshot" of the flow system was then propagated to provide water fluxes for all basins as a function of time, allowing for evolving areas of wetland and lake. The agricultural ecosystem model was treated separately from the natural ecosystem (accumulation) modelling. LDFs in SR-Site were then taken to be the highest values of dose from releases to each of the basins in the landscape over the whole timespan of the simulation. Most of the LDFs used to scale releases from the geosphere in SR-Site come from a single basin in the future landscape; a small part of a larger basin.

That the highest LDF in SR-Site comes from a small part of a larger basin is of interest. It is by no means clear that the hydrological map for the "average object" in Figure 1 is applicable to the conditions relevant to the release location in the portion of the basin that gives rise to the highest LDFs. Similarly the full basin model in GEMA-Site does not necessarily represent the flows in the locality with the highest LDFs. Nevertheless the GEMA-Site approach – which can be configured to represent a broad range of basin geometries allows the key hydrological characteristics to be identified. It is not necessary to model *exactly* the SR-Site case, what is required is to see what features events and processes in a representative landscape combine to give the highest radiological consequences. In this way usage of GEMA-Site here is not bound to the SKB interpretation of the future landscape and its evolution. What is required is a better understanding of groundwater flows in basins in the landscape. Practically this means a clearer, more direct method of translating results from MIKE-SHE (or similar) into the dose assessment modelling framework.

Use of GEMA-Site here provides a useful contrast to SKB's LDF modelling. In SR-Site, SKB construct a complete model of the landscape, with all basins that could potentially become contaminated by receiving a direct release from bedrock fractures modelled as a network of objects. All relevant basins in the future evolution of the future landscape – with compartments linked by a fixed set of relations – are therefore included in the assessment. The GEMA-Site alternative takes a representation of a single basin and uses probabilistic techniques to sample a large volume of phase-space. This reveals the characteristics of the basins that will give rise to doses at the higher end of the range. The basin characteristics included in the SKB landscape model are include within the sample space of the psa.

GEMA-Site has been developed using one of the basins in the future landscape as a template. It is assumed that the FEPs expressed in this basin are representative of those in alternative configurations of the basin. In this way it is possible to model an ensemble of different basins by varying the geometry of the basin. Basins with different geometry produce significantly different dose results. By varying the geometry GEMA-Site can be used to identify those characteristics of the basins in the landscape that will give rise to the highest doses. As might be expected, smaller basins with smaller cultivated areas are associated with the highest doses. This result is similar to that for the most important basin in the SKB analysis.

The evolving flow system in GEMA-Site also produces some further interesting results. The greater the overall catchment collecting water in the basin (as net infiltration) the lower the doses for the less strongly sorbing radionuclides. For more strongly sorbing radionuclides, however, a larger uncontaminated outer basin can increase the dose in the central agricultural basin. The collected net infiltration in the outer basin re-circulates upwards through the central basin acting to remobilise accumulations close to the release areas at the base of the lower regolith increasing activity concentrations of the upper regolith's agricultural soil. This result is characteristic of the hydrology of basins in the low–relief topography towards the Swedish east coast. This feature of the landscape could not be addressed with models in which the flow *vectors* of the regolith hydrology did not change in both magnitude *and* direction during the evolution. Combined with the analysis of SKB's hydrological description in the earlier part of this report, this finding motivates increased utilisation of results from the underlying hydrological model (MIKE-SHE) on which SKB's flow system in their radionuclide transport model is based.

In the GEMA-Site implementation employed here there are three different assumptions concerning water usage during the agricultural period. It is assumed that, sooner or later, the lake at the centre of the basin evolves into a wetland which is no longer useable as a source of drinking water. Prior to this, during the lake phase, lake water can be used.

The first option for agricultural and domestic water is therefore that the water collected in the network of drainage ditches that are used to keep the agricultural land dry enough for cultivation is used as the source of water. Depending on the size of the basin the volumetric flow in the drainage system is potentially large since it carries away the net infiltration in the entire basin.

The second option is that a well in the lower regolith of the central basin This is where the highest accumulations of activity are found. Dilution in this part of the system is less than in the overall drainage system because the well water concentration depends only on the fraction of the total flow in the basin that circulates at the lowest levels of the regolith.

The third option assumes that all drinking water is obtained from uncontaminated sources, implicitly outside the basin. In this case the concentration in water for drinking, domestic and agricultural purposes is zero.

SKB use an alternative assumption for water concentrations. In SR-Site water is assumed to be taken from a bedrock well with "average" well capacity derived from regional well water abstractions. The concentration of well water in this case is based on geosphere rather than biosphere considerations and it is difficult to use concentrations obtained in this way consistently in the context of the unit release from the bedrock assumed in the derivation of LDFs.

Agricultural usage is expected to be restricted to the watering of livestock since this is the practice observed in today's biosphere conditions. The possibility of using the different water sources for irrigation is also considered. Naturally this leads to higher doses for some radionuclides.

The advantage of the GEMA-Site approach to water resource exploitation is that it is based on the sustainability of the basin in respect of the supportable population. In their determination of the supportable population in the modelled basins, SKB focus on the productivity of foodstuffs. This is highest for the agricultural ecosystem. To complement this the sustainable population making use of potential local water resources should also be considered.

6. Conclusions

Suitability of LDFs used in SR-Site

With the additional material from the RFI-process (Request for Further Information) limited improvements have been made to the initial configuration of the alternate model GEMA-Site. This model has been used to explore the potential range of dose consequences in the modelled landscape for comparison with the LDFs generated in SR-Site. The key feature of the alternate model is that the magnitude of water fluxes between specific elements of the basins regolith can change in time as a results of the evolution of the system. A probabilistic sensitivity analysis also allowed the most important features of the GEMA-Site model to be identified. The size of the basins and the water collecting and focusing potential emerge as key to understanding calculated doses.

The calculated LDF values in SR-Site are used to scale discharges from the bedrock fractures to estimate potential radiological impact in the assessment. From the analysis carried out here with GEMA-Site the LDF values calculated for weakly sorbing radionuclides (here ^{79}Se and ^{129}I) would appear to be robust in that the quoted values are close to the top of the range of doses calculate in the probabilistic runs of GEMA-Site.

For the more strongly sorbing radionuclides (^{94}Nb here and the ^{226}Ra chain, including dauhghters ^{210}Pb and ^{210}Po) results from GEMA-Site suggest that the SR-Site LDFs might reasonably be increased. For ^{94}Nb this would be by upto a factor of 50 but for the ^{226}Ra chain more than two order of magnitudes higher values might be possible. This is a consequence of the focusing potential of larger basins forcing the sorbed radionuclides upwards from their initial accumulations in the lower regolith layers of the central basin where input from the bedrock fracture system takes place. The importance of exploitation of local water resources is also noted. Use of shallow (regolith) wells for domestic purposes can give high consequences.

Results here therefore suggest that SKB's assumptions about exploitation of local water resources may not capture the full range of possible human activities and that potential usage of shallow wells should be included in future assessments.

Confidence in SKB's radionuclide transport model

The SKB radionuclide transport model is driven by water fluxes supplied as a result of detailed groundwater flow calculations carried out using MIKE-SHE. Results from these calculations are abstracted and combined before being passed onto the radionuclide transport modellers. This review has not considered the detail work of, or results from, MIKE-SHE. A better understanding of the underlying details of MIKE-SHE would have been very useful to the reviewer.

It has not been possible to verify and justify the parametrisation of the SR-Site radionuclide transport model. Details requested from SKB in the RFI process have not been provided. However, a substantial quantity of data were made available regarding snapshots of water fluxes in those six lakes modelled in MIKE-SHE that were used to define the "average object" and from which parameters subsequently used in the radionuclide transport model were derived.

Though detailed these numerical datasets (six lakes at three times) have not been shown to be suitably representative of any kind of "average object" in the future Forsmark landscape. From the psa results using GEMA-Site, it can be questioned as to whether the “average object” has any real significance in the assessment of dose, particularly as the “average object” characteristics were derived using only the results at a single snapshot at 5000 CE. In any case, review of the details of the six lakes at three times suggests that the 3 kyear interval (2000, 3000 5000 CE) is too short to reveal any major evolutionary trends.

Using the 5000 CE data for the six lakes it has not been possible to reproduce the “average object” flux scheme that SKB used as the basis for the radionuclide transport model. Neither was it possible to further improve the evolutionary sequence of regolith hydrology in GEMA-Site. This affects confidence in the radionuclide transport model as espoused by SKB to its detriment.

Broadly, however, we can be confident that the calculated LDFs do not significantly underestimate the radiological impact of the proposed facility disposal. This conclusion is based on the application of GEMA-Site to provide an alternative set of Dose Assessment Model results.

The use of GEMA-Site has provided a useful alternate viewpoint in the assessment process by which the LDFs themselves can be evaluated and because the procedures involved in developing and configuring the model provide insight in the modelling processes necessary in SR-Site’s dose assessment modelling. Further development of the Alternate model GEMA-Site is recommended to better address vertical exchanges between regolith layers.

Results from GEMA-Site indicate some mechanisms – particularly the focussing effect of water fluxes towards the central, lower elevation, parts of the basin during the evolution – could play a role in leading to higher concentrations and doses from the ^{226}Ra chain. These mechanisms are not represented in the Avila *et al*. (2010) implementation and therefore cannot play influence dose in the SR-Site model.

There is a large amount of detail calculated during the MIKE-SHE modelling of the hydrology. SKB need to make better use of this resource in future assessments – not just for the spent-fuel repository but also for the proposed extension to the SFR low and intermediate-level repository at Forsmark. SSM would benefit from a better understanding of the capabilities and potential of the MIKE-SHE class of modelling.

Requests for Further Information
In respect of the procedure by which Requests for Further Information were submitted to SKB via SSM there are some reservations. The process worked in part. Most of what was requested in respect of the dose assessment modelling was provided. But not all of what was requested. Some of this might have been an oversight by SKB but some was simply postponed and ultimately not delivered. The method was slow and cumbersome and did not provide a means of compelling answers to be provided. A method of requiring SKB to respond in a thorough and timely manner is required.

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Requests for Further Information, Winter 2014

Request 1 – Results for the mass balance of six lakes at three times

Chapter 8 of SKB Report R-10-02 presents a balance scheme for an "average object" based on the combination of water fluxes derived from six lakes close to the Forsmark NPP in the present day (Gunnarsboträsket, Gällsboträsket, Stocksjön, Puttan, Bolundsfjärden and Fiskarfjärden).

Please supply the following details from the MIKE-SHE modelling:

For the times 2000 CE, 3000 CE and 5000 CE **and** for each of the six lakes provide

1. The areas of
   a. catchment (basin)
   b. lake
   c. mire
   d. lake + mire
2. Water fluxes between the compartments used in the MIKE-SHE tool for defining mass balance in compartment models
   a. Volumetric fluxes in m^3 $year^{-1}$
   b. Advective fluxes expressed as mm $year^{-1}$ (as for the "average object" mass balance scheme shown in R-10-02, Fig 8-5.)

In total, then, there should be mass balance schemes for six lakes at each of three times, making 18 sets of results in total.

Results in the form of Fig 8.5 of R-10-02 would be preferable. It is understood, however, that results in the form of Fig 8-4 of R-10-02 (with numerical values attached) would show the same details.

Request 2 – Detailed derivation of parameters in the TR-10-06 radionuclide transport model

Please provide detailed step-by-step description of the procedure used to *justify, define* and *calculate* the numerical values used in the radionuclide transport model for the following six parameters:

i) Upwards velocity out of lower regolith: *adv_low_mid*;
ii) Fraction of flow from lower regolith directed to mire: *fract_mire*;
iii) Net precipitation: *runoff*;
iv) Fraction of infiltration to catchment moving laterally in terrestrial subsystem: *Ter_adv_midup_norm*
v) Fraction of infiltration to catchment moving laterally in aquatic subsystem: *Aqu_adv_midup_norm*
vi) Fractional lateral flux from subcatchment to wetland: *flooding_coef*

Please note that the description in TR-10-01 does not provide sufficient information.

At the meeting on 19 November, an extract from the developer's log relating to these parameters was shown. Please provide a copy of this extract. Note again, however, that the details therein appeared to be insufficient to enable SSM and consultants to verify the actual procedure that was used.

APPENDIX 2

Summary and compilation of SKB's response to the RFI, Autumn 2014

SKB's Response – Covering letter

Svar till SSM på begäran om komplettering rörande radionuklidtransport och dosberäkning med koppling till ythydrologi

Strålsäkerhetsmyndigheten, SSM, har i sin skrivelse till Svensk Kärnbränslehantering AB, SKB, daterad 2014-01-28 (SSM2011-2426-162) begärt svar på kvarstående frågeställningar rörande kopplingen mellan modellen för ytnära hydrologi och modellen för radionuklidtransport som används vid dosberäkningarna (Dokumentnr: SSM2011-1137-53).

SSM begär att SKB lämnar en motivering till användningen av normaliserade flödesfaktorer i radionuklidtransportmodellen. SSM begär också detaljerad information kopplat till beräkningen av de normaliserade flödesfaktorerna för att SSM:s konsulter ska kunna göra egna beräkningar och fortsätta granska kopplingen mellan modellen för ytnära hydrologi och modellen för radionuklidtransport. SSM:s konsulter har uttryckt sin begäran enligt nedan.

1. *"Results for the mass balance of six lakes at three times."*
2. *"Detailed derivation of parameters in the TR-10-06 radionuclide transport model."*

Eftersom en av SSM:s konsulter är engelskspråkig behöver SSM kompletteringen på engelska.

Nedan besvaras fråga 1. Svar på fråga 2 lämnas i september 2014. Så som efterfrågats ges SKB:s svar på engelska.

Request 1 - Results for the mass balance of six lakes at three times
Chapter 8 of SKB Report R-10-02 presents a balance scheme for an "average object" based on the combination of water fluxes derived from six lakes close to the Forsmark NPP in the present day (Gunnarsboträsket, Gällsboträsket, Stocksjön, Puttan, Bolundsfjärden and Fiskarfjärden).

Please supply the following details from the MIKE-SHE modelling:
For the times 2000 CE, 3000 CE and 5000 CE and for each of the six lakes provide

1. *The areas of*
    a. *catchment (basin)*
    b. *lake*
    c. *mire*
    d. *lake + mire*

SKB:s svar
The areas of each lake, mire, and lake + mire are given in R-10-02, Table 8-1, and also in the

enclosed PowerPoint presentation "*Water balances Forsmark*" (slide 2). The same areas are used for all three instances in time, since the same QD model was used in all three models (see R-10-02, page 303). The areas of the catchment (defined as entire catchment above outlet of a lake object) for each of the six objects are given in the PowerPoint presentation "*Water balances Forsmark*" (slide 3). Catchment areas are not estimated directly from the MIKE SHE model, but obtained from GIS shape files (see map on slide 3 in the Powerpoint presentation).

2. *Water fluxes between the compartments used in the MIKE-SHE tool for defining mass balance in compartment models*
   a. *Volumetric fluxes in m^3 year-1*
   b. *Advective fluxes expressed as mm year^{-1} (as for the "average object" mass balance scheme shown in R-10-02, Fig 8-5.)*

In total, then, there should be mass balance schemes for six lakes at each of three times, making 18 sets of results in total.
Results in the form of Fig 8.5 of R-10-02 would be preferable. It is understood, however, that results in the form of Fig 8-4 of R-10-02 (with numerical values attached) would show the same details.

SKB:s svar
All water balances are extracted by the MIKE SHE water balance tool, in the same way as described in R-10-02, Chapter 8, and presented in the enclosed Powerpoint presentation "*Water balances Forsmark*".

Request 2 – Detailed derivation of parameters in the TR-10-06 radionuclide transport model
Please provide detailed step-by-step description of the procedure used to justify, define and calculate the numerical values used in the radionuclide transport model for the following six parameters:

i. *Upwards velocity out of lower regolith: adv_low_mid;*
ii. *Fraction of flow from lower regolith directed to mire: fract_mire;*
iii. *Net precipitation: runoff;*
iv. *Fraction of infiltration to catchment moving laterally in terrestrial subsystem: Ter_adv_midup_norm*
v. *Fraction of infiltration to catchment moving laterally in aquatic subsystem: Aqu_adv_midup_norm*
vi. *Fractional lateral flux from subcatchment to wetland: flooding_coef*

SKB:s svar
Svar på denna fråga lämnas i september 2014

<u>Comments</u>

Request 1
SKB's response to Request 1 is complete and has been useful in developing understanding of how assessment models can be based on detailed site-descriptive models - in this case the underlying MIKE-SHE modelling on which the mass balance schemes used to define parameters in the SR-Site radionuclide transport model are based.

Request 2
Although the response to request 2 was quoted by SKB as being available in September of 2014, no further communication has been received. This is disappointing though not essential. The main aim of the second request was to elucidate why the radionuclide transport model in TR-10-06 (Avila *et al*., 2010) was parameterise din the way it was. At the November 2013 meeting, when the requests for further information were discussed with SKB, extracts of the development log of the model were made available but these did not provide the desired information. Speculation on the basis for the model parameterisation is not required. That SKB have not responded

suggests, however, that revisions to the modelling approach might be forthcoming in future assessments.

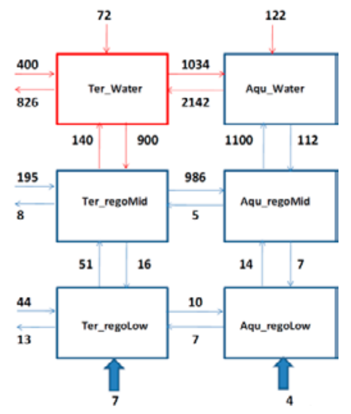
Summary of detail

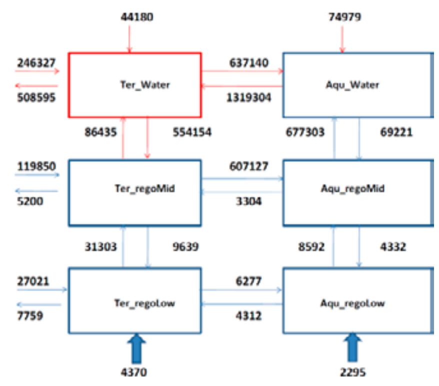
Material in Response 1 comprised information in the form of flux maps for the six lakes combined in Bosson *et al*. (2010) to generate parameters for the model "average object". For the record, the mass balance schemes are reproduced here.:

Lake Bolundsfjärden

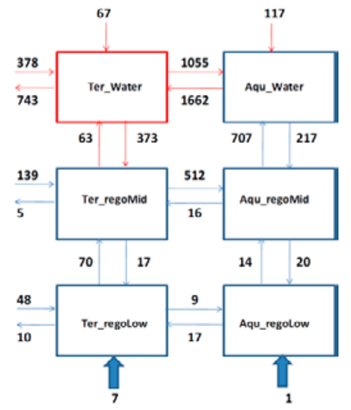
date	fluxes mm year^{-1}	fluxes m^3 year^{-1}

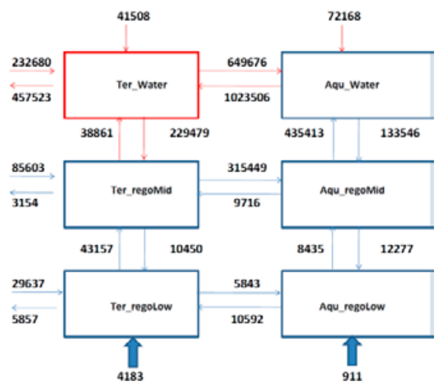
2000 CE



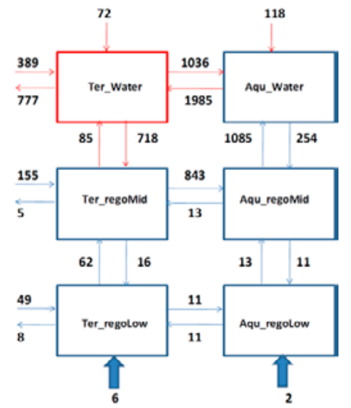


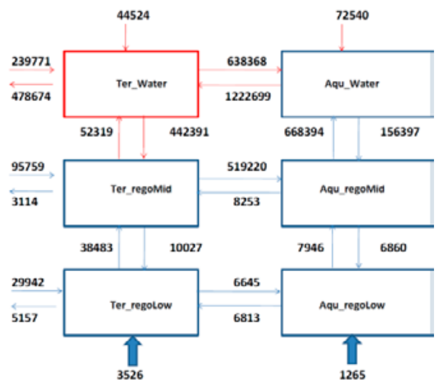
3000 CE





5000 CE

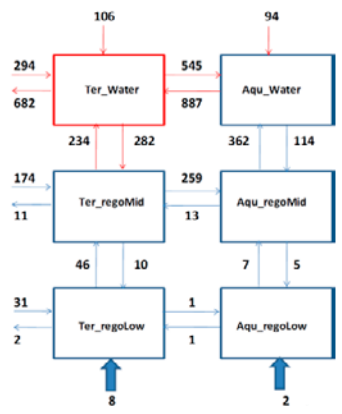


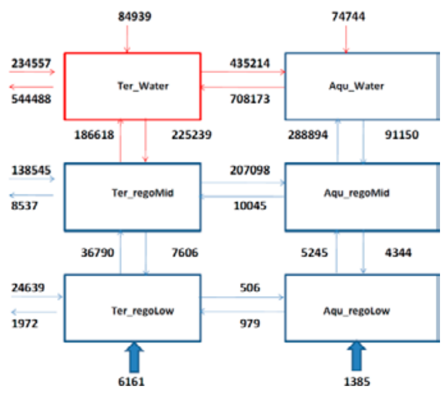


Lake Fiskarfjärden

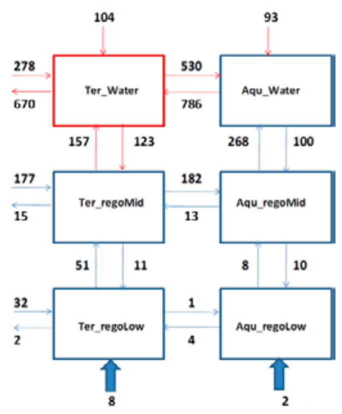
date	fluxes mm year^{-1}	fluxes m^3 year^{-1}

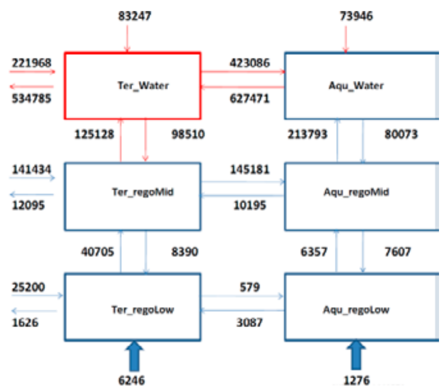
2000 CE





3000 CE





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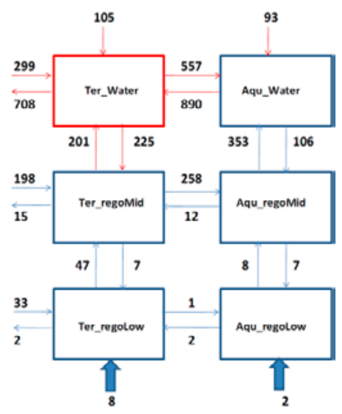

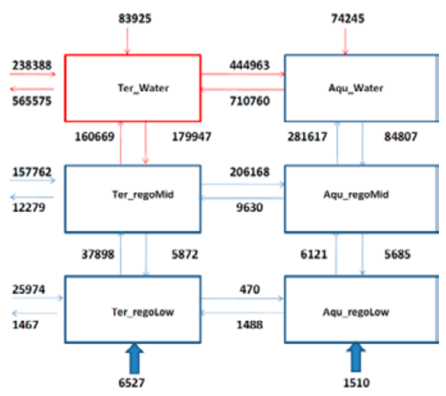

Lake Gunnarsboträsket

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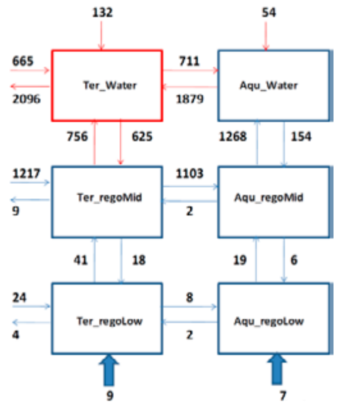
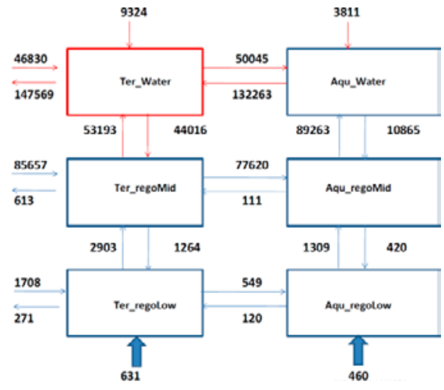
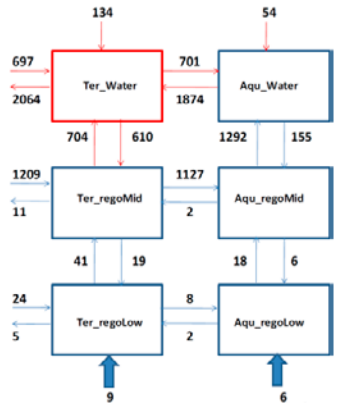
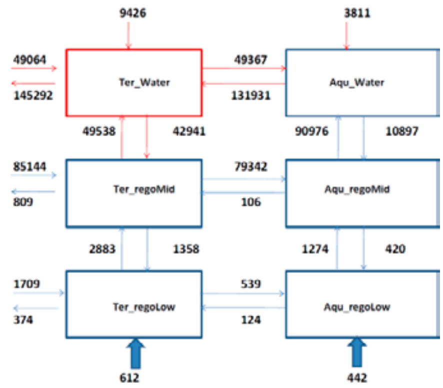
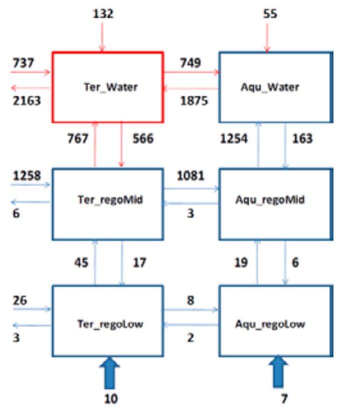
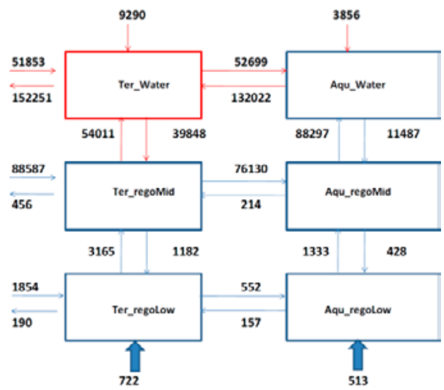
<tr><td>2000 CE</td><td></td><td></td></tr>
<tr><td>3000 CE</td><td></td><td></td></tr>
<tr><td>5000 CE</td><td></td><td></td></tr>
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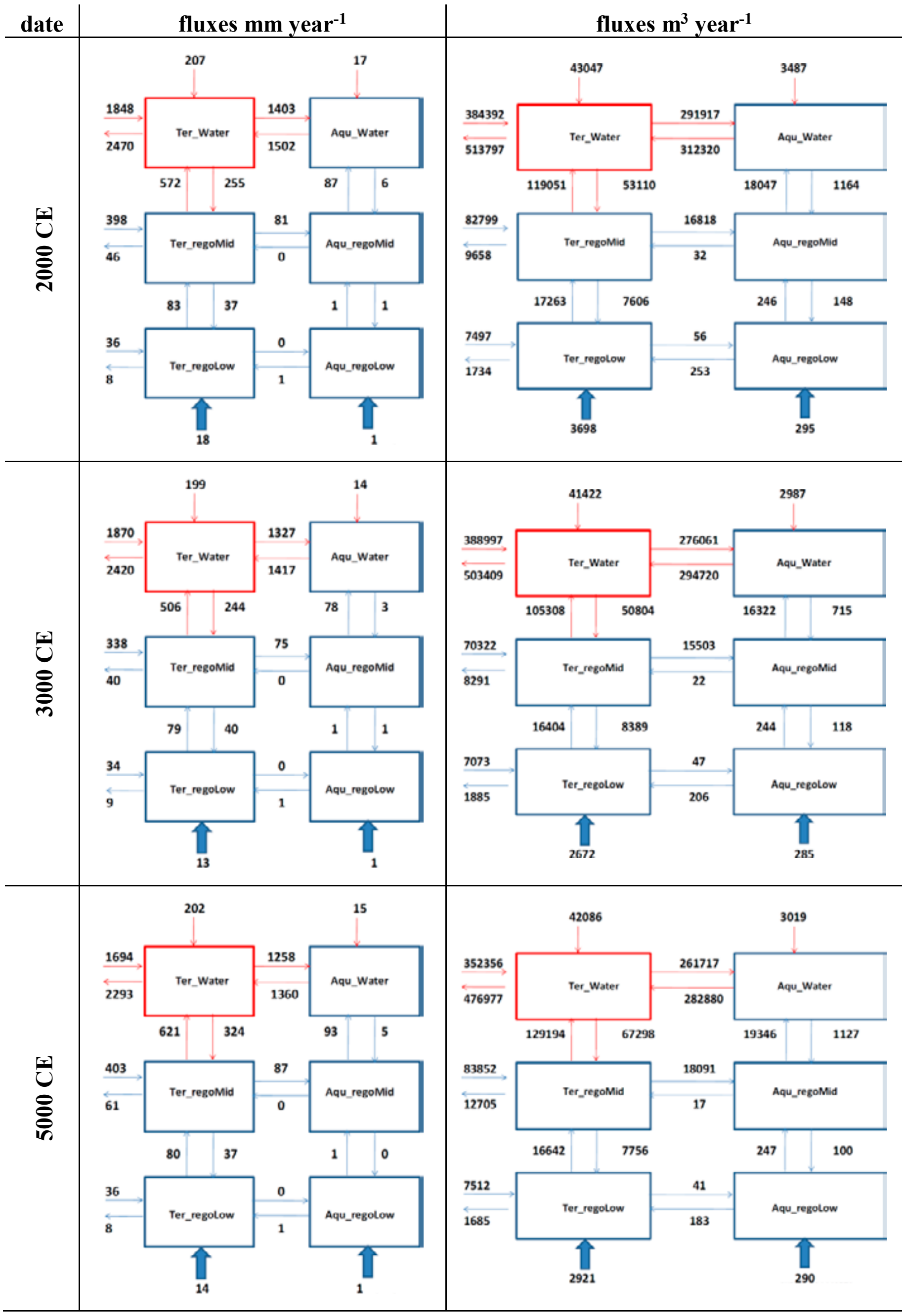
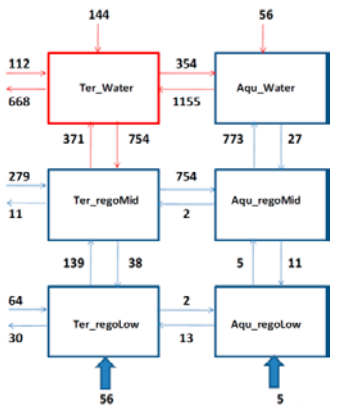
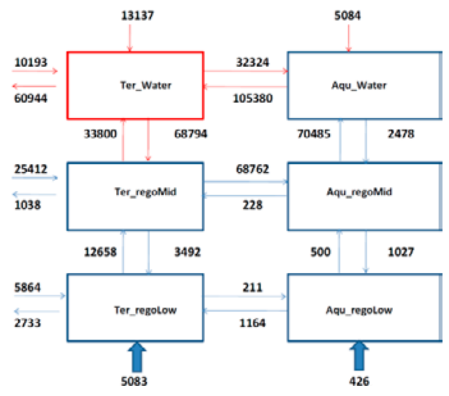
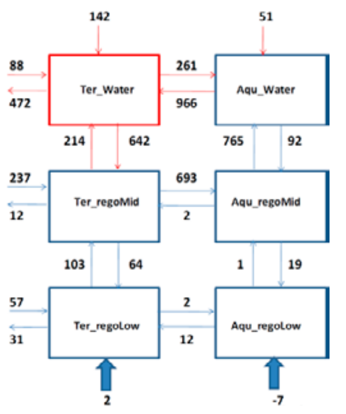
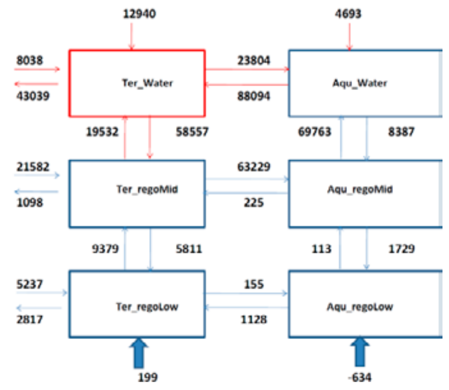
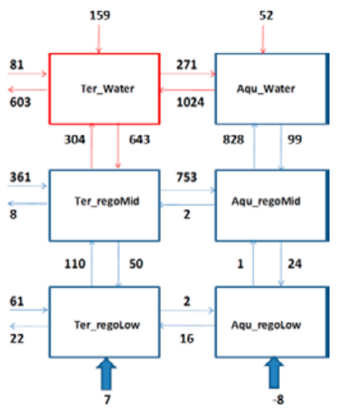
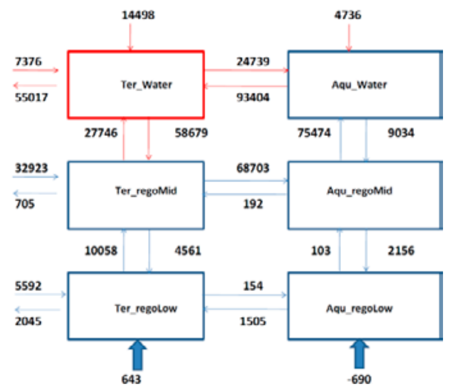
Lake Gällsboträsket



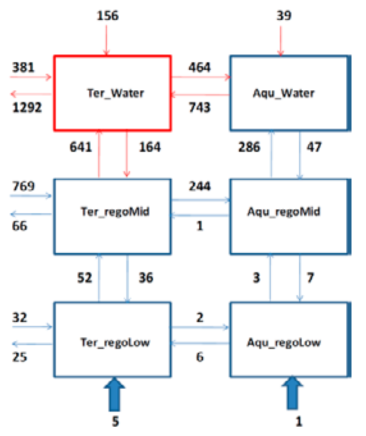
Lake Puttan

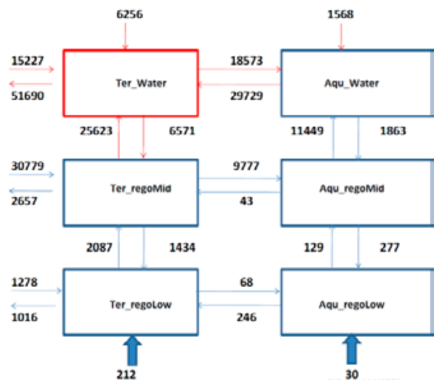
date	fluxes mm year^{-1}	fluxes m^3 year^{-1}
2000 CE		
3000 CE		
5000 CE		

Lake Stocksjön

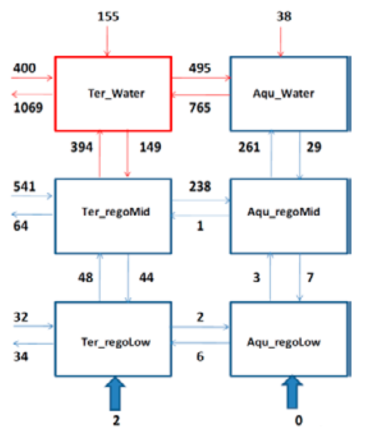
date	fluxes mm year^{-1}	fluxes m^3 year^{-1}

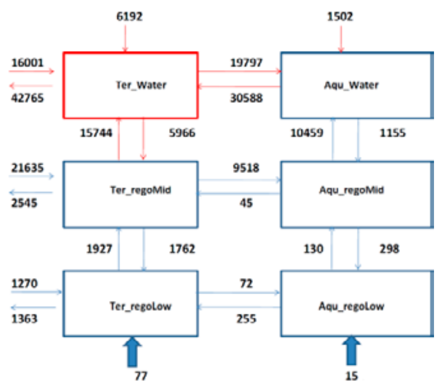
2000 CE



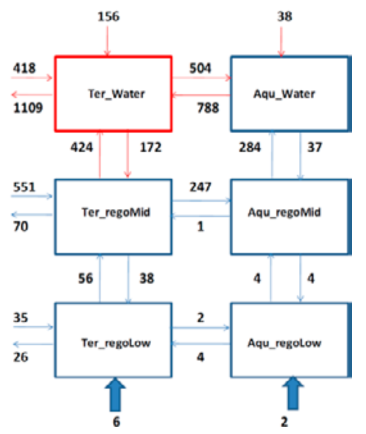


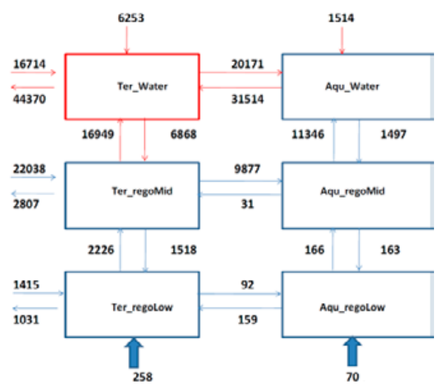
3000 CE





5000 CE





GEMA-Site Reference Case flow system

GEMA-Site is a compartment model with four compartments arranged in a vertical structure representing a specific module of the basin. The lateral extent of the basin is represented by a set of modules. Water and solid material fluxes are expressed for each of eight potential interactions for each compartment, as shown in Figure 15. Lateral transfers between modules are expressed as the up- and downstream fluxes.

To represent the evolving flow system the fluxes for each compartment are encoded in the transport model (in Ecolego) for each of the time periods indicated in Figure 6. Step changes are assumed in this early stage of the modelling. Given the relatively coarse discretisation of the model the only solid material transfers involve sedimentation during the sea and lake phases as well as accumulations of organic material during the wetland stage leading to growth of the upper regolith. The following tables give the calculated water fluxes during each of the periods for the four compartments and each of the three modules (Outer, Inner and Central basins). Numerical values are for the GEMA-Site reference case (see Kłos 2015).

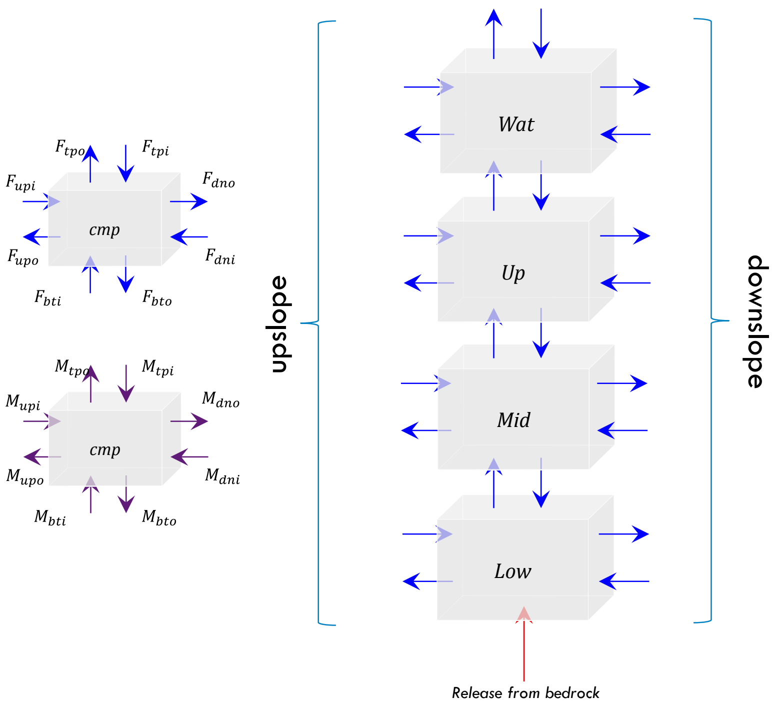


Figure 15: Modular structures of the radionuclide transport model in GEMA-Site. Each compartment in the model has interactions via up- and downslope faces as well as top and bottom faces. The components of the water and solid flux matrices are shown. These combined transfers link the compartments of each module and express fluxes into and out of the combined biosphere module. Application of GEMA-Site takes a number of modules and combines them to represent the spatial discretisation of the system as a function of time.

Water fluxes in the GEMA-Site model are itemised in each of **Error! Reference ource not found.** to Table 7, respectively for the Central basin (where agriculture is assumed), Inner basin and Outer basin. NB this scheme is used for all variants in the probabilistic sensitivity analysis. The relations between fluxes are unchanged, the numerical values of the parameters are sampled. The fluxes calculated from these equations use the data in Table 4. Finally, Table 8 lists the solid material fluxes used in the determination of the transition times. For all other data, see Kłos (2015).

Radionuclide specific parameters and distributions are listed in Table 9 and sampled parameters for the characteristics of the compartments of the basin in Table 10.

Table 4. Drivers for the water fluxes and changes to the flow system (Reference Values).

Parameter		Value	Units
	ldot_uplift	-0.006	m $year^{-1}$
	ETp	0.4	m $year^{-1}$
	Ppt	0.56	m $year^{-1}$
CentralBasin	A_obj_0	100000	m^2
InnerBasin	A_obj_0	1000000	m^2
OuterBasin	A_obj_0	10000000	m^2
	v_geo_sea	0.01	m $year^{-1}$
	v_geo_ter	0.01	m $year^{-1}$
OuterBasin	phi_upp	0.69720186	unitless
OuterBasin	f_phi_mid	0.932811906	unitless
OuterBasin	phi_mid	f_phi_mid*(1.0-phi_upp) 0.282453710	unitless
	pt_agri	19000	year
OuterBasin	t_agri	25000	year (never agriculture)
InnerBasin	t_agri	25000	year (never agriculture)
CentralBasin	t_agri	int(pt_agri)	year

Table 5. Water fluxes in the Central basin.

Water fluxes in the Central basin

Parameter			Ecolego Expression	Outer t < t_sea	Outer t < t_aqu	Inner t < t_sea	Inner t < t_aqu	Central t < t_sea	Central t < t_aqu	Central t_aqu <= t < t_agri	Central t >= t_agr
CentralBasin	lower regolith	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	lower regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	3.4E+04	3.4E+04
CentralBasin	lower regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	3.4E+04	3.4E+04
CentralBasin	lower regolith	F_bti	Centralbasin.v_geo*Centralbasin.A_obj	1.0E+03	1.0E+03	1.0E+03	1.0E+03	1.0E+03	1.0E+03	1.0E+03	1.0E+03
CentralBasin	lower regolith	F_bto	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	lower regolith	F_dni	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	lower regolith	F_dno	if(time < Centralbasin.t_aqu, 0.0, 0.0)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	lower regolith	F_tpi	if(time < Centralbasin.t_aqu, 0.0, Centralbasin.mid_regolith.F_bto)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	lower regolith	F_tpo	if(time < Centralbasin.t_aqu, F_upi + F_bti, F_upi + F_bti)	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	3.4E+04	3.4E+04
CentralBasin	lower regolith	F_upi	if(time < Outerbasin.t_aqu, 0.0, if(time >=Centralbasin.t_agri, Innerbasin.lower_regolith.F_dno, Innerbasin.lower_regolith.F_dno))	0.0	0.0	0.0	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
CentralBasin	lower regolith	F_upo	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	mid regolith	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	mid regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	4.9E+05	5.4E+05
CentralBasin	mid regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	4.9E+05	5.4E+05
CentralBasin	mid regolith	F_bti	if(time < Centralbasin.t_aqu, Centralbasin.lower_regolith.F_tpo, Centralbasin.lower_regolith.F_tpo)	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	3.4E+04	3.4E+04
CentralBasin	mid regolith	F_bto	if(time < Centralbasin.t_aqu, 0.0, 0.0)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	mid regolith	F_dni	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	mid regolith	F_dno	if(time < Centralbasin.t_aqu, 0.0, if(time >=Centralbasin.t_agri, F_upi + F_tpi + F_bti - F_tpo, 0.0))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0E+05
CentralBasin	mid regolith	F_tpi	if(time < Centralbasin.t_aqu, 0.0, Centralbasin.upper_regolith.F_bto)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6E+04
CentralBasin	mid regolith	F_tpo	if(time < Centralbasin.t_aqu, F_bti + F_upi, if(time >=Centralbasin.t_agri, ETp*Centralbasin.A_obj, F_bti + F_upi))	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	4.9E+05	4.0E+04
CentralBasin	mid regolith	F_upi	if(time < Outerbasin.t_aqu, 0.0, Innerbasin.mid_regolith.F_dno)	0.0	0.0	0.0	0.0	0.0	0.0	4.5E+05	4.5E+05
CentralBasin	mid regolith	F_upo	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5. Water fluxes in the Central basin. (continued).

Water fluxes in the Central basin (continued)

Parameter			Ecolego Expression	Outer		Inner		Central			
				t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t_aqu <= t < t_agri	t >= t_agr
CentralBasin	upper regolith	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	upper regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	1.8E+06	9.6E+04
CentralBasin	upper regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	1.8E+06	9.6E+04
CentralBasin	upper regolith	F_bti	Centralbasin.mid_regolith.F_tpo	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	4.9E+05	4.0E+04
CentralBasin	upper regolith	F_bto	if(time < Centralbasin.t_aqu, 0.0, if(time >=Centralbasin.t_agri, F_tpi, 0.0))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6E+04
CentralBasin	upper regolith	F_dni	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	upper regolith	F_dno	if(time < Centralbasin.t_aqu, 0.0, if(time >=Centralbasin.t_agri, 0.0, F_tpi - F_tpo + F_upi + F_bti))	0.0	0.0	0.0	0.0	0.0	0.0	1.8E+06	0.0
CentralBasin	upper regolith	F_tpi	if(time < Centralbasin.t_aqu, 0.0, Ppt*Centralbasin.A_obj + Centralbasin.F_irri - Centralbasin.F_intercept)	0.0	0.0	0.0	0.0	0.0	0.0	5.6E+04	5.6E+04
CentralBasin	upper regolith	F_tpo	if(time < Centralbasin.t_aqu, F_bti + F_upi, ETp*Centralbasin.A_obj)	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	3.4E+04	4.0E+04	4.0E+04
CentralBasin	upper regolith	F_upi	if(time < Outerbasin.t_aqu, 0.0, if(time >=Centralbasin.t_agri, 0.0, Innerbasin.upper_regolith.F_dno))	0.0	0.0	0.0	0.0	0.0	0.0	1.3E+06	0.0
CentralBasin	upper regolith	F_upo	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	water	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	water	F_bal_in	F_tpi + F_bti + F_upi + F_dni	9.4E+08	9.4E+08	9.4E+08	9.4E+08	9.4E+08	5.6E+04	0.0	0.0
CentralBasin	water	F_bal_out	F_tpo + F_bto + F_upo + F_dno	9.4E+08	9.4E+08	9.4E+08	9.4E+08	9.4E+08	5.6E+04	0.0	0.0
CentralBasin	water	F_bti	if(time < Centralbasin.t_aqu, Centralbasin.upper_regolith.F_tpo, 0.0)	1.0E+03	1.0E+03	1.0E+03	3.4E+04	3.4E+04	0.0	0.0	0.0
CentralBasin	water	F_bto	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin	water	F_dni	F_dno - (F_tpi - F_tpo) - F_bti	4.7E+08	4.7E+08	4.7E+08	4.7E+08	4.7E+08	0.0	0.0	0.0
CentralBasin	water	F_dno	if(time < Centralbasin.t_aqu, F_upi + F_bti + F_tpi - F_tpo, 0.0)	4.7E+08	4.7E+08	4.7E+08	4.7E+08	4.7E+08	1.6E+04	0.0	0.0
CentralBasin	water	F_tpi	if(time < Centralbasin.t_aqu, Ppt*Centralbasin.A_obj, 0.0)	5.6E+04	5.6E+04	5.6E+04	5.6E+04	5.6E+04	5.6E+04	0.0	0.0
CentralBasin	water	F_tpo	if(time < Centralbasin.t_aqu, ETp*Centralbasin.A_obj, 0.0)	4.0E+04	4.0E+04	4.0E+04	4.0E+04	4.0E+04	4.0E+04	0.0	0.0
CentralBasin	water	F_upi	if(time <=Centralbasin.t_sea, Centralbasin.A_obj*(l/tau_wat_ret - Centralbasin.v_geo - (Ppt - ETp)), 0.0)	4.7E+08	4.7E+08	4.7E+08	4.7E+08	4.7E+08	0.0	0.0	0.0
CentralBasin	water	F_upo	if(time <=Centralbasin.t_sea, Centralbasin.A_obj*(l/tau_wat_ret - Centralbasin.v_geo - (Ppt - ETp)), 0.0)	4.7E+08	4.7E+08	4.7E+08	4.7E+08	4.7E+08	0.0	0.0	0.0
CentralBasin		F_intercept	if(time < t_agri, 0.0, (n_irri_cereal*lai_cereal*lsc_cereal*area_cereal) + (n_irri_root*lai_root*lsc_root*area_root) + (n_irri_veg*lai_veg*lsc_veg*area_veg))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CentralBasin		F_irri	if(time < t_agri, 0.0, (n_irri_cereal*l_irri_cereal*area_cereal) + (n_irri_veg*l_irri_veg*area_veg) + (n_irri_root*l_irri_root*area_root))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6. Water fluxes in the Inner basin.

Water fluxes in the Inner basin

	Parameter		Ecolego Expression	Outer t < t_sea	Outer t < t_aqu	Inner t < t_sea	Inner t < t_aqu	Central t < t_sea	Central t < t_aqu	Central t_aqu <= t < t_agri	Central t >= t_agr
InnerBasin	lower regolith	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	lower regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	0.0	0.0	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
InnerBasin	lower regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	0.0	0.0	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
InnerBasin	lower regolith	F_bti	Innerbasin.v_geo*Innerbasin.A_obj	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	lower regolith	F_bto	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	lower regolith	F_dni	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	lower regolith	F_dno	if(time < Innerbasin.t_aqu, 0.0, F_upi + F_bti + F_tpi - Innerbasin.F_irri)	0.0	0.0	0.0	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
InnerBasin	lower regolith	F_tpi	if(time < Innerbasin.t_aqu, 0.0, Innerbasin.mid_regolith.F_bto)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	lower regolith	F_tpo	if(time < Innerbasin.t_aqu, F_upi + F_bti, if(time < Centralbasin.t_aqu, 0.0, 0.0))	0.0	0.0	3.3E+04	0.0	0.0	0.0	0.0	0.0
InnerBasin	lower regolith	F_upi	if(time < Outerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, Outerbasin.lower_regolith.F_dno, Outerbasin.lower_regolith.F_dno))	0.0	0.0	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
InnerBasin	lower regolith	F_upo	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	0.0	0.0	4.8E+05	2.1E+06	2.1E+06	1.7E+06	1.7E+06	1.7E+06
InnerBasin	upper regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	0.0	0.0	4.8E+05	2.1E+06	2.1E+06	1.7E+06	1.7E+06	1.7E+06
InnerBasin	upper regolith	F_bti	Innerbasin.mid_regolith.F_tpo	0.0	0.0	4.8E+05	4.5E+05	4.5E+05	0.0	0.0	0.0
InnerBasin	upper regolith	F_bto	if(time < Innerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, F_tpi - F_bti, 0.0))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_dni	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_dno	if(time < Innerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, 0.0, F_tpi - F_tpo + F_upi + F_bti))	0.0	0.0	0.0	1.7E+06	1.7E+06	1.3E+06	1.3E+06	1.3E+06
InnerBasin	upper regolith	F_tpi	if(time < Innerbasin.t_aqu, 0.0, Ppt*Innerbasin.A_obj + Innerbasin.F_irri - Innerbasin.F_intercept)	0.0	0.0	0.0	5.6E+05	5.6E+05	5.6E+05	5.6E+05	5.6E+05
InnerBasin	upper regolith	F_tpo	if(time < Innerbasin.t_aqu, F_bti + F_upi, ETp*Innerbasin.A_obj)	0.0	0.0	4.8E+05	4.0E+05	4.0E+05	4.0E+05	4.0E+05	4.0E+05
InnerBasin	upper regolith	F_upi	if(time < Outerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, 0.0, Outerbasin.upper_regolith.F_dno))	0.0	0.0	0.0	1.1E+06	1.1E+06	1.1E+06	1.1E+06	1.1E+06
InnerBasin	upper regolith	F_upo	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal_in	F_tpi + F_bti + F_upi + F_dni	8.8E+09	8.8E+09	8.8E+09	9.6E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal_out	F_tpo + F_bto + F_upo + F_dno	8.8E+09	8.8E+09	8.8E+09	9.6E+05	0.0	0.0	0.0	0.0

Table 6. Water fluxes in the Inner basin. (continued)

Water fluxes in the Inner basin (continued)

				Outer		Inner		Central			
	Parameter		Ecolego Expression	t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t_aqu <= t < t_agri	t >= t_agr
InnerBasin	water	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal_in	F_tpi + F_bti + F_upi + F_dni	8.8E+09	8.8E+09	8.8E+09	9.6E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal_out	F_tpo + F_bto + F_upo + F_dno	8.8E+09	8.8E+09	8.8E+09	9.6E+05	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_bti	Innerbasin.mid_regolith.F_tpo	0.0	0.0	4.8E+05	4.5E+05	4.5E+05	0.0	0.0	0.0
InnerBasin	upper regolith	F_bto	if(time < Innerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, F_tpi - F_bti, 0.0))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_dni	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	upper regolith	F_dno	if(time < Innerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, 0.0, F_tpi - F_tpo + F_upi + F_bti))	0.0	0.0	0.0	1.7E+06	1.7E+06	1.3E+06	1.3E+06	1.3E+06
InnerBasin	upper regolith	F_tpi	if(time < Innerbasin.t_aqu, 0.0, Ppt*Innerbasin.A_obj + Innerbasin.F_irri - Innerbasin.F_intercept)	0.0	0.0	0.0	5.6E+05	5.6E+05	5.6E+05	5.6E+05	5.6E+05
InnerBasin	upper regolith	F_tpo	if(time < Innerbasin.t_aqu, F_bti + F_upi, ETp*Innerbasin.A_obj)	0.0	0.0	4.8E+05	4.0E+05	4.0E+05	4.0E+05	4.0E+05	4.0E+05
InnerBasin	upper regolith	F_upi	if(time < Outerbasin.t_aqu, 0.0, if(time >=Innerbasin.t_agri, 0.0, Outerbasin.upper_regolith.F_dno))	0.0	0.0	0.0	1.1E+06	1.1E+06	1.1E+06	1.1E+06	1.1E+06
InnerBasin	upper regolith	F_upo	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal	F_bal_out - F_bal_in	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal_in	F_tpi + F_bti + F_upi + F_dni	8.8E+09	8.8E+09	8.8E+09	9.6E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_bal_out	F_tpo + F_bto + F_upo + F_dno	8.8E+09	8.8E+09	8.8E+09	9.6E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_bti	if(time < Innerbasin.t_aqu, Innerbasin.upper_regolith.F_tpo, 0.0)	0.0	0.0	4.8E+05	4.0E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_bto	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_dni	if(time < Innerbasin.t_sea, F_dno - (F_tpi - F_tpo) - F_bti, 0.0)	4.4E+09	4.4E+09	4.4E+09	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_dno	if(time < Innerbasin.t_aqu, F_upi + F_bti + F_tpi - F_tpo, 0.0)	4.4E+09	4.4E+09	4.4E+09	5.6E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_tpi	if(time < Innerbasin.t_aqu, Ppt*Innerbasin.A_obj, 0.0)	5.6E+05	5.6E+05	5.6E+05	5.6E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_tpo	if(time < Innerbasin.t_aqu, ETp*Innerbasin.A_obj, 0.0)	4.0E+05	4.0E+05	4.0E+05	4.0E+05	0.0	0.0	0.0	0.0
InnerBasin	water	F_upi	if(time <=Innerbasin.t_sea, Innerbasin.A_obj*(l/tau_wat_ret - Innerbasin.v_geo - (Ppt - ETp)), 0.0)	4.4E+09	4.4E+09	4.4E+09	0.0	0.0	0.0	0.0	0.0
InnerBasin	water	F_upo	if(time <=Innerbasin.t_sea, Innerbasin.A_obj*(l/tau_wat_ret - Innerbasin.v_geo - (Ppt - ETp)), 0.0)	4.4E+09	4.4E+09	4.4E+09	0.0	0.0	0.0	0.0	0.0
InnerBasin		F_intercept	if(time < t_agri, 0.0, (n_irri_cereal*lai_cereal*lsc_cereal*area_cereal) + (n_irri_root*lai_root*lsc_root*area_root) + (n_irri_veg*lai_veg*lsc_veg*area_veg))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
InnerBasin		F_irri	if(time < t_agri, 0.0, (n_irri_cereal*l_irri_cereal*area_cereal) + (n_irri_veg*l_irri_veg*area_veg) + (n_irri_root*l_irri_root*area_root))	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7. Water fluxes in the Outer basin.

Water fluxes in the Outer basin

Parameter			Ecolego Expression	Outer		Inner		Central			
				t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t_aqu <= t < t_agri	t >= t_agr
OuterBasin	lower regolith	F_bal	F_bal_out - F_bal_in	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	lower regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	0.0E+00	0.0E+00	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
OuterBasin	lower regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	0.0E+00	0.0E+00	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
OuterBasin	lower regolith	F_bti	Outerbasin.v_geo*Outerbasin.A_obj	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	lower regolith	F_bto	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	lower regolith	F_dni	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	lower regolith	F_dno	if(time < Outerbasin.t_aqu, 0.0, F_bti + F_tpi - Outerbasin.F_irri)	0.0E+00	0.0E+00	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
OuterBasin	lower regolith	F_tpi	if(time < Outerbasin.t_aqu, 0.0, Outerbasin.mid_regolith.F_bto)	0.0E+00	0.0E+00	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
OuterBasin	lower regolith	F_tpo	if(time < Outerbasin.t_aqu, F_bti, 0.0)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	lower regolith	F_upi	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	lower regolith	F_upo	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_bal	F_bal_out - F_bal_in	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_bal_in	F_tpi + F_bti + F_upi + F_dni	0.0E+00	0.0E+00	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05
OuterBasin	upper regolith	F_bal_out	F_tpo + F_bto + F_upo + F_dno	0.0E+00	0.0E+00	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05
OuterBasin	upper regolith	F_bti	if(time < Outerbasin.t_aqu, Outerbasin.lower_regolith.F_tpo, 0.0)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_bto	if(time < Outerbasin.t_aqu, 0.0, F_tpi - F_dno)	0.0E+00	0.0E+00	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04	3.3E+04
OuterBasin	upper regolith	F_dni	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_dno	if(time < Outerbasin.t_aqu, 0.0, Outerbasin.phi_mid*(Outerbasin.upper_regolith.F_tpi - Outerbasin.upper_regolith.F_tpo))	0.0E+00	0.0E+00	4.5E+05	4.5E+05	4.5E+05	4.5E+05	4.5E+05	4.5E+05
OuterBasin	upper regolith	F_tpi	if(time < Outerbasin.t_aqu, 0.0, Outerbasin.upper_regolith.F_bto)	0.0E+00	0.0E+00	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05
OuterBasin	upper regolith	F_tpo	if(time < Outerbasin.t_aqu, F_bti, 0.0)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_upi	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_upo	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Table 7. Water fluxes in the Outer basin. (continued).

Water fluxes in the Outer basin (continued)

Parameter			Ecolego Expression	Outer		Inner		Central			
				t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t < t_sea	t < t_aqu	t_aqu <= t < t_agri	t >= t_agr
OuterBasin	water	F_bal	F_bal_out - F_bal_in	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_bal_in	F_tpi + F_bti + F_upi + F_dni	0.0E+00	0.0E+00	5.6E+06	5.6E+06	5.6E+06	5.6E+06	5.6E+06	5.6E+06
OuterBasin	water	F_bal_out	F_tpo + F_bto + F_upo + F_dno	0.0E+00	0.0E+00	5.6E+06	5.6E+06	5.6E+06	5.6E+06	5.6E+06	5.6E+06
OuterBasin	upper regolith	F_bti	if(time < Outerbasin.t_aqu, Outerbasin.mid_regolith.F_tpo, 0.0)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_bto	if(time < Outerbasin.t_aqu, 0.0, (1.0 - Outerbasin.phi_upp)*(F_tpi - F_tpo))	0.0E+00	0.0E+00	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05
OuterBasin	upper regolith	F_dni	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_dno	if(time < Outerbasin.t_aqu, 0.0, Outerbasin.phi_upp*(F_tpi - F_tpo))	0.0E+00	0.0E+00	1.1E+06	1.1E+06	1.1E+06	1.1E+06	1.1E+06	1.1E+06
OuterBasin	upper regolith	F_tpi	if(time < Outerbasin.t_aqu, 0.0, Ppt*Outerbasin.A_obj + Outerbasin.F_irri - Outerbasin.F_intercept)	0.0E+00	0.0E+00	5.6E+06	5.6E+06	5.6E+06	5.6E+06	5.6E+06	5.6E+06
OuterBasin	upper regolith	F_tpo	if(time < Outerbasin.t_aqu, F_bti, ETp*Outerbasin.A_obj)	0.0E+00	0.0E+00	4.0E+06	4.0E+06	4.0E+06	4.0E+06	4.0E+06	4.0E+06
OuterBasin	upper regolith	F_upi	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	upper regolith	F_upo	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_bal	if(time < Outerbasin.t_aqu, Outerbasin.mid_regolith.F_tpo, 0.0)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_bal_in	if(time < Outerbasin.t_aqu, 0.0, (1.0 - Outerbasin.phi_upp)*(F_tpi - F_tpo))	0.0E+00	0.0E+00	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05	4.8E+05
OuterBasin	water	F_bal_out	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_bti	F_bal_out - F_bal_in	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_bto	F_tpi + F_bti + F_upi + F_dni	4.5E+10	5.6E+06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_dni	F_tpo + F_bto + F_upo + F_dno	4.5E+10	5.6E+06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_dno	if(time < Outerbasin.t_aqu, Outerbasin.upper_regolith.F_tpo, 0.0)	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_tpi	0	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_tpo	F_dno - (F_tpi - F_tpo)	4.1E+09	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_upi	if(time <=Innerbasin.t_sea, Innerbasin.A_obj*(l/tau_wat_ret - Innerbasin.v_geo - (Ppt - ETp)), 0.0)	4.1E+09	1.6E+06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin	water	F_upo	if(time < Outerbasin.t_aqu, Ppt*Outerbasin.A_obj, 0.0)	5.6E+06	5.6E+06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin		F_intercept	if(time < Outerbasin.t_aqu, ETp*Outerbasin.A_obj, 0.0)	4.0E+06	4.0E+06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
OuterBasin		F_irri	if(time <=Outerbasin.t_sea, Outerbasin.A_obj*(l/tau_wat_ret - Outerbasin.v_geo - (Ppt - ETp)), 0.0)	4.1E+10	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Table 8. Solid material fluxes (kg year[-1]) and their parameterisation (non-zero fluxes only). Mass transfers are set to dynamic equilibrium at the bed sediment of aquatic systems, sedimentation and resuspension rates are set equal. Accumulation of organic material during lake and wetland periods is assumed to be atmospheric carbon via vegetation that is not included in the dynamic transport model.

Parameter			expression
Central	water	M_bti	if(time < CentralBasin.t_aqu, CentralBasin.sed_upp*CentralBasin.A_obj, 0.0)
	water	M_bto	if(time < CentralBasin.t_aqu, CentralBasin.sed_ned*CentralBasin.A_obj, 0.0)
	Upper regolith	M_tpi	if(time < CentralBasin.t_aqu, CentralBasin.water.M_bto, 0.0)
	Upper regolith	M_tpo	if(time < CentralBasin.t_aqu, CentralBasin.water.M_bti, 0.0)
Inner	Water	M_bti	if(time < InnerBasin.t_aqu, InnerBasin.sed_upp*InnerBasin.A_obj, 0.0)
	Water	M_bto	if(time < InnerBasin.t_aqu, InnerBasin.sed_ned*InnerBasin.A_obj, 0.0)
	Upper regolith	M_tpi	if(time < InnerBasin.t_aqu, InnerBasin.water.M_bto, 0.0)
	Upper regolith	M_tpo	if(time < InnerBasin.t_aqu, InnerBasin.water.M_bti, 0.0)
Outer	Water	M_bti	if(time < OuterBasin.t_aqu, OuterBasin.sed_upp*OuterBasin.A_obj, 0.0)
	Water	M_bto	if(time < OuterBasin.t_aqu, OuterBasin.sed_ned*OuterBasin.A_obj, 0.0)
	Upper regolith	M_tpi	if(time < OuterBasin.t_aqu, OuterBasin.water.M_bto, 0.0)
	Upper regolith	M_tpo	if(time < OuterBasin.t_aqu, OuterBasin.water.M_bti, 0.0)

			Outer	Inner	Central	
	Parameter		*t < t_aqu*	*t < t_aqu*	*t < t_aqu*	*t >= t_aqu*
Central	water	M_bti	3.0E+03	3.0E+03	3.0E+03	0
	water	M_bto	3.0E+03	3.0E+03	3.0E+03	0
	Upper regolith	M_tpi	3.0E+03	3.0E+03	3.0E+03	0
	Upper regolith	M_tpo	3.0E+03	3.0E+03	3.0E+03	0
Inner	Water	M_bti	3.0E+04	3.0E+04	0	0
	Water	M_bto	3.0E+04	3.0E+04	0	0
	Upper regolith	M_tpi	3.0E+04	3.0E+04	0	0
	Upper regolith	M_tpo	3.0E+04	3.0E+04	0	0
Outer	water	M_bti	3.0E+05	0	0	0
	water	M_bto	3.0E+05	0	0	0
	Upper regolith	M_tpi	3.0E+05	0	0	0
	Upper regolith	M_tpo	3.0E+05	0	0	0

Table 9. Sampled radionuclide specific parameters in the sensitivity analysis. Reference case and geometric means values modified from report TR-10-07 (Nordén *et al.*, 2010).

Parameter	Radio-nuclide	RC	Distribution	GM	GSD
k_d inorganic material	^{79}Se	2.20E-02	lognormal	2.20E-02	2.6
m^3 kg^{-1}	^{94}Nb	1.90E+00		1.90E+00	5.3
TR-10-07 Table 3-1	^{129}I	7.10E-03		7.10E-03	5.1
	^{226}Ra	7.30E+00		7.30E+00	2.2
	^{210}Po	2.10E-01		1.90E-01	5.0
	^{210}Pb	7.70E+00		7.70E+00	5.4
k_d organic material	Se-79	5.30E-01	lognormal	2.30E-01	3.8
m^3 kg^{-1}	Nb-94	4.00E+01		4.00E+01	3.8
TR-10-07 Table 3-2	I-129	7.10E-01		2.40E-01	7.6
	Ra-226	2.30E+00		2.30E+00	2.1
	Po-210	6.60E+00		6.60E+00	5.0
	Pb-210	4.30E+01		2.80E+01	5.8
k_d marine ecosystems	Se-79	3.40E+00	lognormal	3.40E+00	16
m^3 kg^{-1}	Nb-94	2.00E+02		2.00E+02	4.7
TR-10-07 Table 3-3	I-129	3.30E+00		3.30E+00	2.1
	Ra-226	4.00E+00		4.00E+00	3.1
	Po-210	2.00E+04		2.00E+04	3.2
	Pb-210	2.50E+02		2.50E+02	2.7
k_d freshwater ecosys-tems	Se-79	8.40E+00	lognormal	8.40E+00	2.1
m^3 kg^{-1}	Nb-94	2.30E+02		2.30E+02	3.2
TR-10-07 Table 3-4	I-129	1.00E+01		1.00E+01	3.7
	Ra-226	7.40E+00		7.40E+00	3.1
	Po-210	1.00E+01		1.00E+01	3.2
	Pb-210	5.40E+02		5.40E+02	2.9

Parameter	Radio-nuclide	RC	Distribution	GM	GSD
CR game	Se-79	4.31E+01	lognormal	2.11E+01	1.2
kg dw kg^{-1} dw	Nb-94	4.57E-01		2.33E-01	3.4
TR-10-07 Table 4-10	I-129	2.16E+00		7.48E-01	1.3
	Ra-226	8.54E-01		4.09E-01	1.1
	Po-210	4.14E+01		2.11E+01	5.5
	Pb-210	8.11E-02		4.14E-02	5.5
CR B35:B106natural	Se-79	2.24E+01	lognormal	6.12E+00	2.4
kg dw kg^{-1} dw	Nb-94	2.04E-03		2.04E-03	3.5
TR-10-07 Table 4-2	I-129	2.86E-01		4.39E-01	4.8
	Ra-226	7.14E-02		7.14E-02	4.6
	Po-210	1.22E-01		1.22E-01	4.2
	Pb-210	1.07E-02		1.07E-02	2.4
CR mush	Se-79	2.02E+01	lognormal	5.52E+00	2.4
kg dw kg^{-1} dw	Nb-94	1.84E-03		1.84E-03	3.5
TR-10-07 Table 4-6	I-129	3.08E-02		3.08E-02	2.3
	Ra-226	2.71E+00		2.71E+00	4.6
	Po-210	1.10E-01		1.10E-01	4.2
	Pb-210	1.20E-02		1.20E-02	2.4

Table 9. Sampled radionuclide specific parameters in the sensitivity analysis. Reference case and geometric means values modified from report TR-10-07 (Nordén *et al.*, 2010). (Continued.)

Parameter	Radio-nuclide	RC	Distribution	GM	GSD
CR pasture	^{79}Se	2.24E+01	lognormal	6.12E+00	2.4
kg dw kg^{-1} dw	^{94}Nb	2.04E-03		2.04E-03	3.5
TR-10-07 Table 4-2	^{129}I	2.86E-01		4.39E-01	4.8
	^{226}Ra	7.14E-02		7.14E-02	4.6
	^{210}Po	1.22E-01		1.22E-01	4.2
	^{210}Pb	1.07E-02		1.07E-02	2.4
CR cereal	^{79}Se	2.27E+01	lognormal	5.78E+00	2.4
kg dw kg^{-1} dw	^{94}Nb	1.38E-02		7.11E-03	1.9
TR-10-07 Table 4-3	^{129}I	1.16E-01		1.16E-01	3.2
	^{226}Ra	1.69E-02		1.69E-02	12.0
	^{210}Po	2.36E-04		2.36E-04	1.01
	^{210}Pb	1.11E-02		1.11E-02	3.6
CR root	^{79}Se	1.99E+01	lognormal	5.61E+00	2.4
kg dw kg^{-1} dw	^{94}Nb	4.18E-03		4.18E-03	14
TR-10-07 Table 4-4	^{129}I	1.02E-01		1.02E-01	14
	^{226}Ra	1.02E-02		1.02E-02	6.8
	^{210}Po	2.81E-03		2.81E-03	5.8
	^{210}Pb	1.58E-03		1.58E-03	7.4
CR veg	^{79}Se	3.42E+01	lognormal	9.18E+00	2.4
kg dw kg^{-1} dw	^{94}Nb	2.14E-02		2.14E-02	1.3
TR-10-07 Table 4-5	^{129}I	3.11E-01		3.11E-01	3.7
	^{226}Ra	1.38E-01		1.38E-01	6.7
	^{210}Po	1.12E-02		1.12E-02	6.9
	^{210}Pb	1.22E-01		1.22E-01	13
TF milk	^{79}Se	4.00E-03	lognormal	4.00E-03	1.8
day kg^{1} fw	^{94}Nb	4.10E-07		4.10E-07	5.8
TR-10-07 Table 4-7	^{129}I	5.40E-03		5.40E-03	2.9
	^{226}Ra	3.80E-04		3.80E-04	2.0
	^{210}Po	2.10E-04		2.10E-04	1.4
	^{210}Pb	1.90E-04		1.90E-04	3.7
TF meat	^{79}Se	1.50E-02	lognormal	1.40E-03	3.9
day kg^{1} fw	^{94}Nb	2.60E-07		2.60E-07	7.9
TR-10-07 Table 4-8	^{129}I	6.70E-03		6.70E-03	2.1
	^{226}Ra	1.70E-03		1.70E-03	7.9
	^{210}Po	5.00E-03		1.70E-03	1.7
	^{210}Pb	7.00E-04		7.00E-04	1.7

Table 9. Sampled radionuclide specific parameters in the sensitivity analysis. Reference case and geometric means values modified from report TR-10-07 (Nordén *et al.*, 2010). (Continued.)

Parameter	Radio-nuclide	RC	Distribution	GM	GSD
CR fish (marine)	^{79}Se	2.16E+01	lognormal	2.16E+01	1.9
kg dw kg^{-1} dw	^{94}Nb	7.65E-02		7.65E-02	2.1
TR-10-07 Table 5-10	^{129}I	4.95E-02		4.95E-02	2.1
	^{226}Ra	3.29E-01		3.29E-01	3.1
	^{210}Po	8.55E+00		8.55E+00	2.0
	^{210}Pb	2.12E-01		2.12E-01	6.1
CR crustacea	^{79}Se	1.66E+01	lognormal	1.66E+01	1.2
kg dw kg^{-1} dw	^{94}Nb	2.81E+00		2.81E+00	2.3
TR-10-07 Table 5-5	^{129}I	6.48E-01		6.48E-01	3.5
	^{226}Ra	8.64E-02		4.32E+00	1.5
	^{210}Po	4.32E+01		4.32E+01	1.2
	^{210}Pb	1.66E+01		1.66E+01	4.6
CR fish freshwater	^{79}Se	1.50E+01	lognormal	1.50E+01	2.9
kg dw kg^{-1} dw	^{94}Nb	9.68E-02		9.68E-02	7.3
TR-10-07 Table 5-6	^{129}I	1.32E-01		1.32E-01	2.8
	^{226}Ra	2.55E-02		8.36E-02	5.5
	^{210}Po	8.80E-01		8.80E-01	2.1
	^{210}Pb	1.19E-01		1.19E-01	2.9

Table 10. Characteristics of the compartments in the modules of the basin. Data are modified from TR-10-01 (Löfgren, 2010) and TR-10-02 (Aquilonius (2010). Other parameters are assumed for GEMA-Site on the basis of the analysis in Kłos (2015).

Name	Unit	Value	PDF	Min	Max	Reference
Area Central basin	m^2	100000	uniform	5.0E+03	1.0E+05	assumed
Area Inner basin	m^2	1000000	uniform	1.0E+03	1.0E+06	assumed
Area Outer basin	m^2	10000000	uniform	1.0E+04	1.0E+07	assumed
porosity agricultural soil	m^3 m^{-3}	0.81	uniform	0.77	0.85	TR-10-01, p337
porosity glacial clay	m^3 m^{-3}	0.64	uniform	0.55	0.75	TR-10-02, p388
porosity peat	m^3 m^{-3}	0.89	uniform	0.76	0.95	TR-10-01, p338
porosity till	m^3 m^{-3}	0.21	uniform	0.18	0.27	TR-10-02, p389
ϕ_{upp}^{Outer}	-	0.697202	uniform	0.2	0.5	assumed
p_{θ}^{agri}	-	0.740741	uniform	0.5	0.95	assumed
f_{ϕ}^{mid}	-	0.932812	uniform	0.4	0.6	assumed
$p_{t_{agri}}$	year	19000	uniform	11200	20000	assumed

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