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Technical Note

2015:48

Supplementary review of SKB's further RFI response

Main Review Phase

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SSM:s 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 granska SKB:s svar på den kompletterande information som begärts av SSM om härledning av flödesrelaterade parametrar. Parametrarna härleds från ythydrologisk modellering och används i radionuklidtransport- och dosberäkningsmodellerna.

Författarnas sammanfattning

Som en del i SSM:s granskningsprocess för SKB:s ansökan om licens för att bygga ett djupt geologiskt slutförvar för använt kärnbränsle i Forsmark (SR-Site) har SSM begärt ytterligare information ("requests for further information", RFI) av SKB. Denna kompletterande rapport behandlar SKB:s slutliga svar på RFI om modelleringsfrågor av radionuklidtransport i biosfären som SSM fick i juni 2015.

Radionuklidtransport- och dosberäkningsmodellen i SR-Site är baserad på en hydrologisk modell som i sin tur är baserad på detaljerad platskarakterisering. Av intresse i denna del av granskningen är det förfarande genom vilket den detaljerade platsbeskrivande modelleringen översätts till hur hydrologin utvecklas med tiden i radionuklidtransportmodellen. Det är flera steg i detta förfarande, vart och ett med tillhörande approximationer och förenklingar.

I rapporten jämförs den detaljerade beskrivningen av hydrologin i det "genomsnittliga objektet" (det så kallade referensfallet), som används av SKB för att approximera generiska hydrologiska egenskaper för avrinningsområdet i det framtida Forsmarkslandskapet, med strukturen och den algebraiska beskrivningen av flödena i radionuklidtransportmodellen. Motiveringen till modelleringsförenklingarna som SKB har genomfört i detta förfarande undersöks. Den implementerade hydrologin i radionuklidtransportmodellen har tydliga skillnader jämfört med det "genomsnittliga objektets" hydrologi.

För att undersöka effekterna av dessa skillnader på beräknade doser i radionuklidtransport- och dosberäkningsmodellen presenteras en uppsättning resultat som jämför fördelningen av radionuklider i den modellerade biosfären. Tre olika implementeringar av radionuklidtransportmodellen utvärderas, var och en med en egen tolkning av hydrologin:

- modellen med vattenflöden som tagits direkt från det “genomsnittliga objektet” - referensfallet,
- modellen med vattenflöden som härletts från SKB:s algebraiska approx imation av det “genomsnittliga objektet”, och
- modellen med objektspecifika vattenflöden för valda avrinnings-området tagna från den detaljerade hydrologiska modellen av Forsmarksområdet.

Resultaten tyder på att doserna som beräknats från den algebraiska abstraktionen av det “genomsnittliga objektet” skulle likna de doser som fås om vid ett fullständigt genomförande av det “genomsnittliga objektets” hydrologi, trots att flödessystemen är olika till sin struktur. Det finns en liten icke-konservativ bias i SKB:s radionuklidtransportmodell för svagare sorberande radionuklider.

När SKB:s radionuklidtransportmodell jämförs med flöden från specifika objekt visar resultaten större avvikelser. Det är därför tydligt att användningen av det “genomsnittliga objektet” i SR-Site inte ger en adekvat representation av viktiga aspekter av hydrologi i radionuklidtransport- och dosberäkningsmodellerna.

Resultaten innebär inte nödvändigtvis ett ogiltigförklarande av de resultat som presenteras i SR-Site, men visar att för framtida biosfärsmodellering, skulle förtroendet för modelleringen kunna förbättras genom en bättre beskrivning av radionuklidtransport och ackumulation i radionuklidtransport- och dosberäkningsmodellerna.

Project information

Kontaktperson på SSM: Shulan Xu
Diarienummer ramavtal: SSM2011-592
Diarienummer avrop: SSM2014-1147
Aktivitetsnummer: 3030012-4401

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.

Objective

The general objective of the project is to review SKB's response to the complementary information requested by SSM regarding the derivation of flow related parameters. The parameters are derived from surface hydrological modelling and used in the biosphere radionuclide transport model.

Summary by the authors

As part of the review process implemented by SSM in respect of SKB's license application for construction of a deep geologic final repository for spent nuclear fuel at Forsmark (SR-Site) a number of requests for further information (RFIs) were submitted by SSM to SKB. This supplementary report deals with SKB's final response to the biosphere and dose assessment modelling RFIs that was received in June 2015.

The dose assessment modelling in SR-Site is based on a hydrological model that is itself based on detailed site characterisation. Of interest in this part of the review is the procedure by which the detailed site descriptive modelling is translated into the representation of evolving hydrology used in the radionuclide transport sub-model of the dose assessment model. There several steps in this procedure, each with associated approximations and simplifications.

This report compares the detailed description of the hydrology of the "average object" (known as the reference case) as used by SKB to approximate generic hydrological characteristics of basins in the future Forsmark landscape, with the structure and algebraic description of the fluxes in the radionuclide transport model. The justification of the modelling simplifications implemented by SKB in this procedure are examined. The implementation of hydrology in the radionuclide transport model has clear differences when compared to the reference "average object" hydrology.

To examine the impact of these differences on calculated doses in the dose assessment model a set of results are presented that compare the distribution of radionuclides in the modelled biosphere. Three different implementations of the radionuclide transport model are evaluated, each with a different interpretation of the hydrology:

- the model using water fluxes taken directly from the “average object” – the reference case,
- the model using water fluxes derived from SKB’s algebraic approxima tion of the “average object”, and
- the model using object specific water fluxes for selected basins taken from the detailed hydrological model of the Forsmark region.

Results indicate that the doses calculated from the algebraic abstraction of the “average object” would be similar to those from the full implementation of the “average object” hydrology, despite the flow systems being different in structure. There is a slight non-conservative bias in the SKB radionuclide transport model for the more weakly sorbing radionuclides.

When the SKB radionuclide transport model is compared with to full flux maps from specific objects the results show greater discrepancies. It is therefore clear the use of the “average object” in SR-Site does not give an adequate representation of key aspects of the hydrology in respect of dose assessment calculations.

The results do not necessarily invalidate the results presented in SR-Site but indicate that, for future assessments, confidence in the modelling would be enhanced by a better description of radionuclide transport and accumulation in the dose assessment model.

Project information
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Contents

1. Introduction and overview

This note gives a supplementary review of material provided by SKB on 19-05-2015 (SKB, 2015ab), following the completion of the final report on the SR-Site. The material deals with the response to the Requests for Further Information (RFI, see Appendix 1). SKB's initial response dealt with Request 1 and was received in July 2014. The new material relates to the procedure for estimating water fluxes and associated transfer rate coefficients in the Avila *et al.* (2010) dose assessment model.

The request is formulated as:

Please provide detailed step-by-step description of the procedure used to *justify*, *define* and *calculate* the numerical values used in the radionuclide transport (RNT) 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*

The hydrological information provided by SKB in the SR-Site documentation is in the form of the "average object" from Bosson *et al.* (2010). The numerical values are shown in Figure 1. These are translated into the algebraic expressions for the fluxes for indicated in Figure 2. This is the representation of the water fluxes included in the Pandora[1] model. This document goes some way to explain how the model used in the dose calculations (with water fluxes expressed in Figure 2) is related to the hydrological basis of the "average object" shown in Figure 1.

The issue addressed in SKB's response is the relationship between the numerical values in Figure 1 and the algebraic expressions for the parameters in Figure 2. The expressions and parameters are listed in Table 1. It is the relationship and, specifically, the justification of Table 1 and Figure 2 on the basis of Figure 1 that was the prompt for the RFI. The explanation in Avila *et al.* was insufficient.

There are three stages in understanding how the "average object" numerical data are used in the SR-Site model:

1. Translation of the flux map in Figure 1 to the fluxes as modelled in Figure 2. Clearly not all the fluxes identified in the "average object" are implemented in the dose model.
2. Assignment of numerical values from the "average object" fluxes to the fluxes in the transport model.
3. Derivation of the normalised fluxes that are used in the Avila *et al.* model itself. Step 2 uses fluxes as numerical values in mm year^{-1}, the transport model (known as the "Pandora model" in SKB, 2015a) uses one absolute flux (adv_low_mid m year^{-1}) and four normalised values ($fract_{mire}$, f_{flood}, $Ter\_adv\_mid\_up\_norm$ and $Aqu\_adv\_mid\_up\_norm$).

These addressed in the analysis section, that follows. Numerical implications follow in Section 3.

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[1] Pandora is the modelling tool used to implement the SKB model.

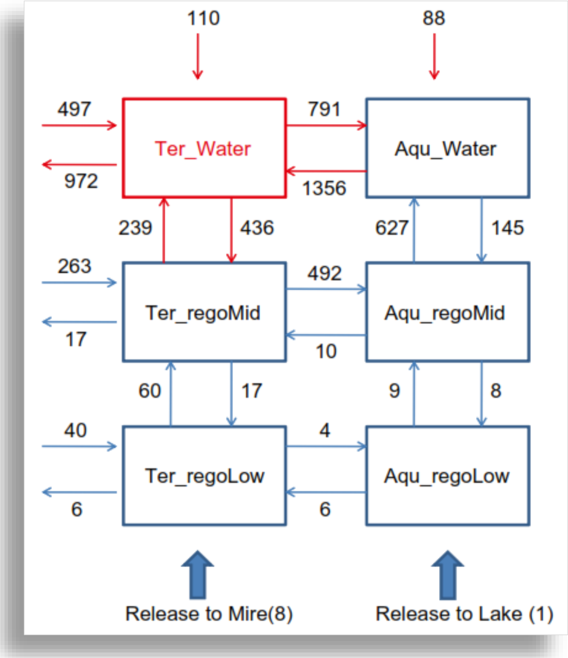


Figure 1. Advective fluxes (F_{ij}) for an average lake-mire object obtained from the MIKE SHE simulations. Values of area normalized fluxes are given in units of mm/year (SKB, 2015a).

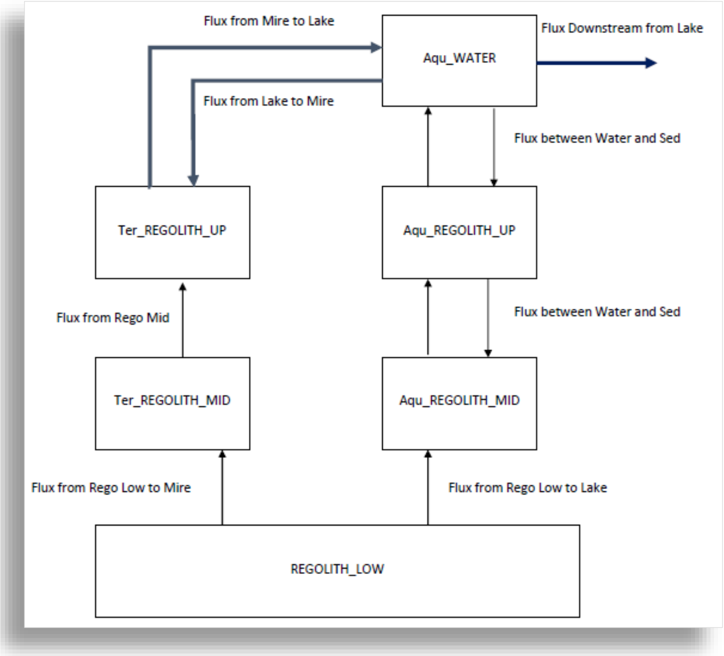


Figure 2. Conceptual representation of the water fluxes included in the Pandora implementation of the SR-Site radionuclide transport model (RNT - SKB, 2015a). These are the fluxes *as used* in the RNT and are denoted in the analysis here as Φ_{ij}. The algebraic expressions for these fluxes are given in Table 1.

Table 1. Summary of algebraic expression for the water fluxes in the Avila *et al*. (2010) radionuclide transport model shown in Figure 2 (SKB, 2015a). Numerical values are quoted in Table 2 of SKB (2015a).

Water flux, Φ_{ij} in RNT model	Parameterisation / description
Flux from Mire to Lake	$\Phi_{\substack{TerUp \\ \to AquWat}} = \left(1+f_{flood}\right)*\frac{area_{catch}}{area_{obj}}*runoff$
Flux from Lake to Mire	$\Phi_{\substack{AquWat \\ \to TerUp}} = f_{flood}*\frac{area_{catch}}{area_{obj}}*runoff$
Flux from Regolith Mid	$\Phi_{\substack{TerMid \\ \to TerUp}} = Ter\_adv\_mid\_up\_norm*\frac{area_{catch}}{area_{obj}}*runoff$
Flux between water and sediment	$\Phi_{\substack{AquMid \\ \to AquUp}} = Aqu\_adv\_mid\_up\_norm*\frac{area_{catch}}{area_{obj}}*runoff$
Flux downstream from lake	$\Phi_{\substack{AquWat \\ \to Downstream}} = \frac{area_{watershed}}{area_{obj}}*runoff$
Flux from Regolith Low to Mire	$\Phi_{\substack{Low \\ \to TerMid}} = fract_{mire}*adv\_low\_mid$
Flux from Regolith Low to Lake	$\Phi_{\substack{Low \\ \to AquMid}} = \left(1-fract_{mire}\right)*adv\_low\_mid$
adv_low_mid	is the area normalized total advective flux from the rego_low to the Ter_rego_mid and Aqu_rego_mid (m/y) = 0.044 m year^{-1}
$fract_{mire}$	is the fraction of the advective flux from the rego_low that goes to the mire (-) = 0.98 unitless
$Ter\_adv\_mid\_up\_norm$	is the advective flux in the terrestrial object from the rego_mid to the rego_up normalized by the net lateral advective fluxes from the mire (-) = 0.30 unitless
$Aqu\_adv\_mid\_up\_norm$	is the advective flux in the aquatic object between the rego_mid and the rego_up and between the rego_up and the water normalized by the net lateral advective fluxes from the mire (-) = 0.64 unitless
f_{flood}	is a coefficient used to calculate the flux from the lake to the mire by flooding (-) = 1.5 (unitless)

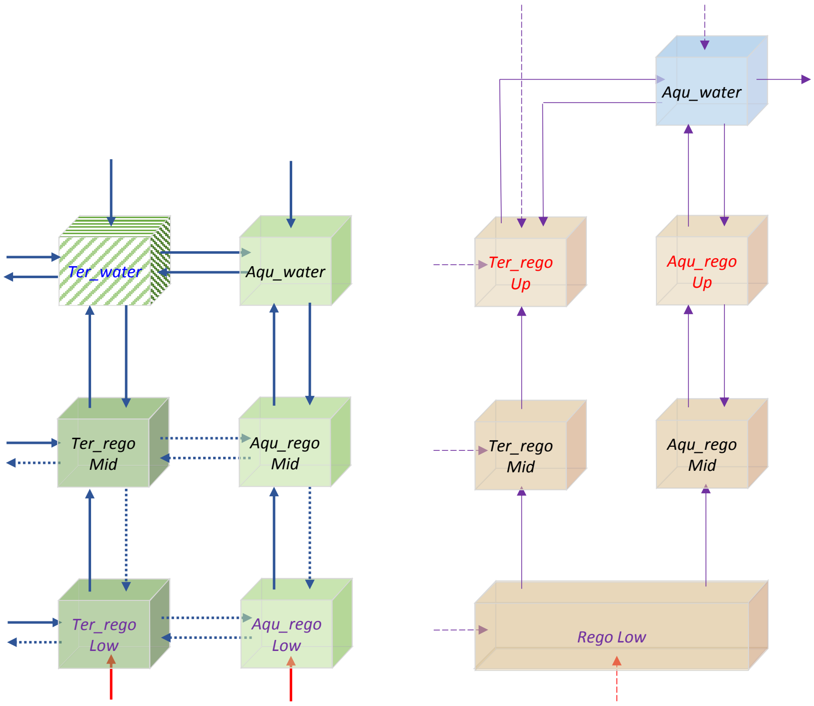
2. Analysis

2.1. Mapping the “average object” to the RNT model

Figure 3 provides a side-by-side comparison of the Bosson *et al.* (2010) “average object” and the Avila *et al.* (2010) RNT model. This emphasises the differences – there are missing compartments, additional compartments, combined compartments as well as missing fluxes. Making sense of the translation of water fluxes from “average object” to RNT model is the aim. Kłos *et al.* (2014) have covered this material already (that analysis was the reason for the RFI in the first place) but there is additional material in SKB (2015a).

In brief, there is not a single compartment-to-compartment interaction in the “average object” that has a direct correspondence in the RNT model. Only the two mid-regolith layers are common, one each for the terrestrial and aquatic sub-models.

There is no interaction between the terrestrial and aquatic mid and upper regolith. In contract there is “instantaneous” interaction between the lower regolith in the aquatic and terrestrial systems – ie contents of these compartments are combined.



“Average object”

RNT model

Figure 3. Comparison of compartment and fluxes: Bosson et al. (2010) “average object” (left) and Avila et al. (2010) RNT model (right). With reference to the “average object”, the cross-hatched compartment is not included in the RNT model, dotted fluxes are *not* included in the RNT model. With reference to the RNT model, the compartments denoted by red text are not present in the “average object”, and the purple regolith low compartment is an amalgamation of the two lower regolith compartments. Dashed fluxes are implied from the “average object” and the red fluxes are the inputs of radionuclides.

2.2. Combining fluxes from the “average object”

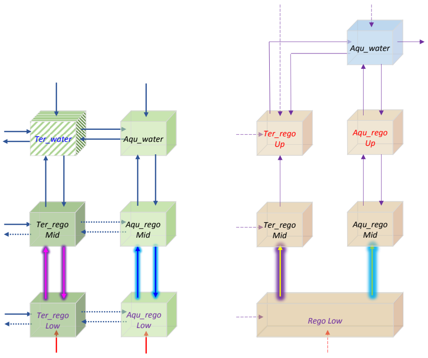
How the fluxes in the “average object” are combined to generate the RNT model parameterisation is crucial to understanding and building confidence in the SR-Site dose assessment model. Because the mapping outlined above is so obscure the usage of the water fluxes in from the “average object” is now addressed in detail.

In the RNT model a total of 10 fluxes are defined. These are considered in turn using the fluxes from the “average object” in Figure 1.

1. **Flux from lower regolith to mire**
   This is the balance between the upwards and downwards fluxes from the terrestrial lower regolith and the terrestrial mid-regolith (purple arrows):

$$\begin{aligned}\Phi_{\substack{Low\\ \to TerMid}} &= F_{\substack{TerLow\\ \to TerMid}} - F_{\substack{TerMid\\ \to TerLow}} \text{ mm year}^{-1} \\ &= 60-17=43\end{aligned} \qquad (1)$$

   This is at least clear, it is the net upward flux from the terrestrial lower regolith.

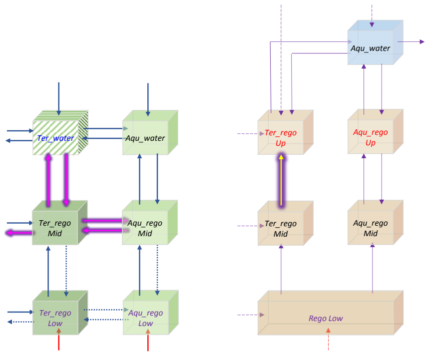


2. **Flux from lower regolith low to lake**
   Similarly this is the net upward flux between the compartments on the aquatic side of the flux map (blue arrows):

$$\begin{aligned}\Phi_{\substack{Low\\ \to AquMid}} &= F_{\substack{AquLow\\ \to AquMid}} - F_{\substack{AquMid\\ \to AquLow}} \text{ mm year}^{-1}. \\ &= 9-8=1\end{aligned} \qquad (2)$$

   By combining the two lower regolith compartments, SKB treat the exchange between them as, effectively, instantaneous. The total net inflow to the lower regolith is 44 mm year^{-1} (see Kłos *et al*. 2014 for the analysis). Most of this flow arises from the subcatchment and only a small fraction from the bedrock with the mire receiving the majority of the flow. Mixing between the two lower regolith domains is indicated as being relatively slow. The combination of the two layers is not well motivated but may not have significance for the dose modelling.

3. **Total flux out of the mid-regolith**
   According to SKB (2015a), the flux from the terrestrial mid-regolith to the terrestrial upper regolith (TerMid to TerUp) is as shown. It combines the net lateral exchange with the aquatic mid regolith and the inflow from the terrestrial water compartment less the loss to the lower regolith. It neglects the input from the subcatchment as well as the input from the lower regolith. There remains some ambiguity here, since the numerical values for the flow out of TerMid to Low is the same as the downstream loss.



The description of this flux in SKB (2015a) states that the flux from RegoMid is "Net flux from Regolith Mid to Regolith Up of the mire plus Net flux from Regolith Mid of the mire to the lake":

$$\begin{aligned}\Phi_{\substack{TerMid\\ \to TerUp}} &= F_{\substack{TerMid\\ \to TerWat}} + F_{\substack{TerMid\\ \to AquMid}} + F_{\substack{TerMid\\ \to Downstream}} - F_{\substack{TerWat\\ \to TerMid}} - F_{\substack{AquMid\\ \to TerMid}} \text{ mm year}^{-1}. \\ &= 239 + 492 + 17 - 436 - 10 = 302\end{aligned} \qquad (3)$$

It is not clear where the figure of $F_{\substack{TerMid\\ \to Downstream}}$ = 17 mm year^{-1}, comes from as a "net flux" and many of the fluxes associated with TerMid are neglected for undocumented reasons. It is further claimed that "this is the total net flux from RegoMid shown in Figure 2 (here)". It is *defined* as this flux in Figure 2 but it is hard to see how this is justified.

Neither is it clear why this upwards flux is represented by a combined net flux including the net flow from TerMid to AquMid. In fact what is used is a *partial* mass balance on the fluxes associated with the terrestrial mid regolith. It is not clear why the other three fluxes are neglected. If all "net fluxes" are added in this way, the result is the mass balance equation for the terrestrial mid regolith:

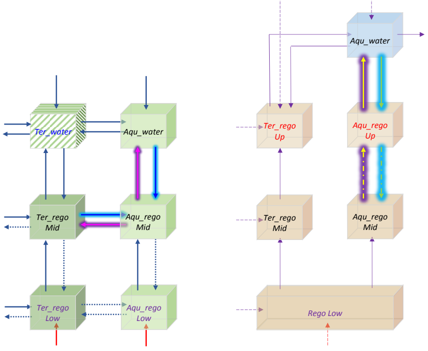
$$\begin{aligned}\Phi_{\substack{TerMid\\ \to TerUp}} &= F_{\substack{TerMid\\ \to TerWat}} + F_{\substack{TerMid\\ \to AquMid}} + F_{\substack{TerMid\\ \to Low}} + F_{\substack{TerMid\\ \to subCatch}} \\ &\quad - F_{\substack{TerWat\\ \to TerMid}} - F_{\substack{AquMid\\ \to TerMid}} - F_{\substack{Low\\ \to TerMid}} - F_{\substack{subCatch\\ \to TerMid}} \text{ mm year}^{-1}. \\ &= 239 + 492 + 17 + 17 - 436 - 10 - 60 - 263 = -4\end{aligned} \qquad (4)$$

This small negative flux is a consequence of rounding errors in Figure 1. The total should be zero. SKB's selective use of some but not all "net fluxes" has no physical meaning and use in this way remains unclear.

Justification for this flux determination is lacking. In comparison to the evaluation of the flux from the lower regolith to the mire or lake, where both are evaluated as a *net upwards* flux, the flow upwards from the terrestrial mid-regolith is confused, being neither the result of mass balance calculation nor a net flux.

We therefore consider that this flux is unreliable. It is not appropriate to estimate the "total flux out of the mid-regolith" in this way. The RFI was intended to obtain the justification for this approach and so has not been fulfilled. SKB have again shown *what* was done but not *why* it was done in this way.

4. **Flux between water and sediment ≡ flux between sediment and lake**
These two fluxes are assumed to be in balance. This is despite there being no aquatic upper regolith in the "average object". Nevertheless it can be assumed that the water flux from the mid regolith passes through the upper regolith before entering the water column; SKB (2015a) states "The same flux values are used between the lake Regolith Up and Water and between lake Regolith up and lake Regolith mid". The fluxes are calculated in two



ways: i) the total flux leaving the Aqu_regoMid compartment:

$$\Phi_{\substack{AquMid\\ \to AquUp}} = \Phi_{\substack{AquUp\\ \to AquWat}} = F_{\substack{AquMid\\ \to AquWat}} + F_{\substack{AquMid\\ \to TerMid}} = 627 + 10 = 637 \text{ mm year}^{-1}, \tag{5a}$$

or ii) the flux entering it:

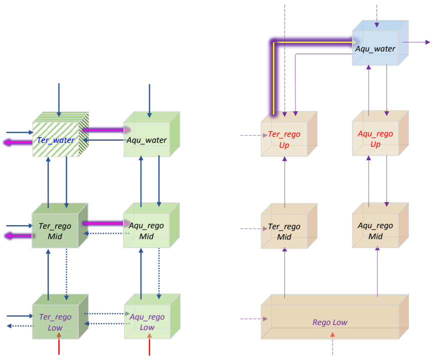
$$\Phi_{\substack{AquWat\\ \to AquUp}} = \Phi_{\substack{AquUp\\ \to AquMid}} = F_{\substack{AquWat\\ \to AquMid}} + F_{\substack{TerMid\\ \to AquMid}} = 145 + 492 = 637 \text{ mm year}^{-1}. \tag{5b}$$

Both formulations neglect the small exchange of the aquatic mid-regolith with the lower aquatic regolith.

So, the numerical values of the exchange between the lake and the sediment (both upper and middle layers) are evaluated using the exchange with the terrestrial system but there is no terrestrial ↔ aquatic exchange in the transport model. This is a modelling assumption – that there are no interactions between the terrestrial and aquatic regolith. The basis of the numerical value used in the aquatic sediment ↔ lake water exchange is not explained.

5. **Flux from mire to lake**

This transfer concerns the lateral transfer of water from the mire to the lake. This presumably means drainage from the mire to the lake. As shown, the value used in the RNT model does not account for the sources of the water flows involved.

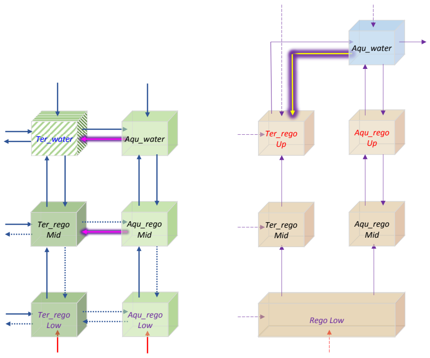


The flux in the RNT model is defined as the combined flow out of the terrestrial mid-regolith and terrestrial water[2] compartments in the MIKE-SHE mass balance scheme. Again there is the implication of mixing between the terrestrial and aquatic mid-regolith layers, despite there being no transport mechanism included in the RNT. The flux from mire to lake is therefore

$$\Phi_{\substack{TerUp\\ \to AquWat}} = F_{\substack{TerWat\\ \to AquWat}} + F_{\substack{TerWat\\ \to Downstream}} + F_{\substack{TerMid\\ \to AquMid}} + F_{\substack{TerMid\\ \to Downstream}} \text{ mm year}^{-1}. \tag{6}$$

$$= 791 + 972 + 492 + 17 = 2272$$

It is not immediately clear why downstream fluxes are included in this definition.



6. **Flux from lake to mire**

This is the reverse process, explained by Avila *et al*. (2010) as flooding. In terms of the MIKE-SHE output it corresponds to an exchange between the water column of the lake and the water compartment of the mire. It is not clear that this

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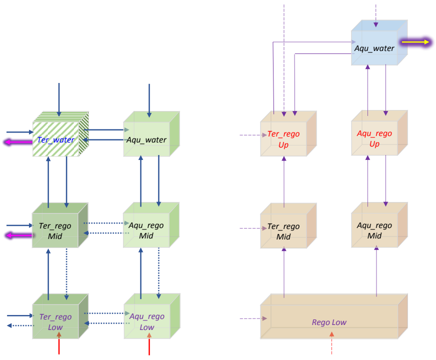
[2] The terrestrial water compartment is interpreted here as the porewater of the upper regolith in wetlands plus any standing water that might occasionally manifest.

is exactly flooding. In such circumstances the “flooding” of the mire would result from a rise in the water table above the land surface, a flow from the regolith not necessarily from the lake. The numerical value of the flux is therefore.

$$\Phi_{\substack{AquWat\\ \to TerUp}} = F_{\substack{AquWat\\ \to TerWat}} + F_{\substack{AquMid\\ \to TerMid}} = 1356 + 10 = 1366 \text{ mm year}^{-1}. \tag{7}$$

7. **Flux downstream from lake**
   This is one of the more straightforward to understand fluxes in the translation between the MIKE-SHE and RNT model structures. It is the flux that drains from the *whole* basin. This is the total flow out of the whole basin (neglecting the drainage from the lower regolith of only 6 mm year^{-1}).



$$\begin{aligned}\Phi_{\substack{AquWat\\ \to downstream}} &= F_{\substack{TerWat\\ \to Downstream}} + F_{\substack{TerMid\\ \to Downstream}} \text{ mm year}^{-1}.\\ &= 972 + 17 = 989\end{aligned} \tag{8}$$

2.3. Numerical values for RNT model parameterisation

The relationship between the water fluxes used in Avila *et al.*’s (2010) RNT model (the Φ_{ij} mm year^{-1}) and the corresponding advective water fluxes in the “*average object*” (the F_{ij} mm year^{-1}) has been reviewed in the preceding section. The relationship between the two sets of numerical fluxes illustrates the approximations to the “*average object*” hydrology needed to define the RNT model. In principle, the full water balance map for different objects in the MIKE-SHE could be used in the landscape modelling. Practically this would require a large and complex database describing water fluxes for future objects. This would complicate an already complex and data intensive landscape model. SKB reasonably conclude that such an approach is not justified. The use of the “*average object*” and the RNT model derived from it is SKB’s attempt to simplify the procedure.

The numerical relationships in Section 2.2 are not the end of the story, however. So that the “*average object*” object fluxes can be used to describe the hydrology of other basins at other times SKB make a further set of assumptions by which the numerical relations are *parameterised*. These resulting equations are those listed in Table 1, together with the parameters used to characterise the generic basin.

SKB provide no discussion of the derivation of the expressions in Table 1 so they must be taken as a statement of what was assumed. Table 1 also lists the numerical values of the five parameters. The origin of these values (in terms of the F_{ij} of the “*average object*”) is given by Löfgren (2010) and Avila *et al.* (2010), albeit with some differences. If the algebraic expressions are accepted for the parameterisation of the Φ_{ij} then, with the alternative interpretation of the Φ_{ij} and F_{ij} in Section 2.2, we are in a position to check the derived numerical values for the five parameters: adv_low_mid, $fract_{mire}$, f_{flood} and the two fluxes that provide the net upward flows from the mid regolith in the aquatic and terrestrial compartments,

$Ter\_adv\_mid\_up\_norm$ and $Aqu\_adv\_mid\_up\_norm$. Doing so builds confidence in the generic modelling carried out with the RNT model.

The approach taken is to recombine the equations in Table 1 to isolate the unknown parameters in terms of the Φ_{ij} and thereby the F_{ij}. From these relations, the numerical values of the model parameters can be obtained.

We start with the flux from lower regolith to each of the terrestrial and aquatic mid-regolith compartments.

1. $fract_{mire}$ - flows from lower regolith to terrestrial and aquatic sub-models

From Table 1, $\Phi_{\substack{Low\\ \to TerMid}} = fract_{mire} * adv\_low\_mid$. Combining this with Equation (1), above, gives

$$fract_{mire} = \frac{\Phi_{\substack{Low\\ \to TerMid}}}{adv\_low\_mid} = \frac{F_{\substack{TerLow\\ \to TerMId}} - F_{\substack{TerMId\\ \to TerLow}}}{adv\_low\_mid} . \tag{9}$$

The net advective flux out of the mire (adv_low_mid) is the net value from the two lower regolith compartments in Figure 1, and this is confirmed on page 342 of Löfgren,

$$adv\_low\_mid = F_{\substack{TerLow\\ \to TerMId}} - F_{\substack{TerMId\\ \to TerLow}} + F_{\substack{AquLow\\ \to AquMId}} - F_{\substack{AquMId\\ \to AquLow}} . \tag{10}$$

Both the original Löfgren (2010) and SKB (2015a) expressions are then confirmed:

$$\begin{aligned} fract_{mire} &= \frac{\Phi_{\substack{Low\\ \to TerMid}}}{adv\_low\_mid} = \frac{F_{\substack{TerLow\\ \to TerMId}} - F_{\substack{TerMId\\ \to TerLow}}}{F_{\substack{TerLow\\ \to TerMId}} - F_{\substack{TerMId\\ \to TerLow}} + F_{\substack{AquLow\\ \to AquMId}} - F_{\substack{AquMId\\ \to AquLow}}} , \\ &= 0.98 \end{aligned} \tag{11}$$

as stated in Table 1. In this way the RNT model parameters are related to the “average object” fluxes. The flow to the aquatic side of the model is therefore characterised by $1 - fract_{mire}$.

NB, this partitioning of the flux from the lower regolith is independent of the size of the overall catchment and the areas of terrestrial and aquatic ecosystems.

2. f_{flood} - exchange between lake and upper terrestrial regolith

In contrast to the fluxes in the lower, mid-regolith sub-system, fluxes in the rest of the model are related directly to the relative areas of the total catchment, the area of the object (combined terrestrial and aquatic models) and the runoff (net infiltration). Water fluxes in the model are therefore linked to the collecting power of the basin. The total meteoric water entering the object can be written as

$$\Phi_{meteo} = \frac{area_{catch}}{area_{obj}} * runoff . \tag{12}$$

This quantity appears in the expressions for the parameter f_{flood} in the RNT model parameterisation in Table 1, so that, written in terms of the Φ_{ij} in Section 2.2, we have

$$f_{flood} = \frac{\Phi_{\substack{AquWat\\ \to TerUp}}}{\Phi_{\substack{TerUp\\ \to AquWat}} - \Phi_{\substack{AquWat\\ \to TerUp}}} .$$

With the fluxes defined in Equations (5) and (6), this gives

$$\begin{aligned} f_{flood} &= \frac{F_{\substack{AquMid\\ \to TerMid}} + F_{\substack{AquWat\\ \to TerWat}}}{F_{\substack{TerWat\\ \to AquWat}} - F_{\substack{AquWat\\ \to TerWat}} + F_{\substack{TerMid\\ \to AquMid}} - F_{\substack{AquMid\\ \to TerMid}} + F_{\substack{TerWat\\ \to Downstream}} + F_{\substack{TerMid\\ \to Downstream}}} . \\ &= 1.51 \end{aligned} \tag{13}$$

This differs from the parameterisation in Löfgren, where p344 gives the equivalent expression:

$$\begin{aligned} f_{flood}\Big|_{Löfgren,(2015)} &= \frac{F_{\substack{TerWat\\ \to AquWat}} + F_{\substack{TerMid\\ \to AquMid}}}{F_{\substack{TerWat\\ \to Downstream}} + F_{\substack{TerMid\\ \to Downstream}}} , \\ &= 1.30 \end{aligned} \tag{14}$$

using the numerical fluxes described in the previous section. SKB (2015a) say that this parameter has a value of 1.5, close to the derived value here and p344 of Löfgren gives a value of 1.1. There is some uncertainty in this parameter.

3. $Ter\_adv\_mid\_up\_norm$ - flow in the terrestrial mid-regolith

This parameter scales the captured runoff according to the flow out of the Ter_Mid compartment. Essentially the total net infiltration (runoff) in the basin is partitioned as a flux between the mire and the lake. Accepting the combination of fluxes in the “average object” model, the meteorological flux in Equation (12) can be used to define this parameter in the model by setting

$$\frac{\Phi_{\substack{AquWat\\ \to TerUp}}}{f_{flood}} = \frac{\Phi_{\substack{TerMid\\ \to TerUp}}}{Ter\_adv\_mid\_up\_norm} .$$

From Equations (3), (7) and (13):

$$\begin{aligned} &Ter\_adv\_mid\_up\_norm \\ &= \frac{F_{\substack{TerMid\\ \to TerWat}} + F_{\substack{TerMid\\ \to AquMid}} + F_{\substack{TerMid\\ \to Low}} - F_{\substack{TerWat\\ \to TerMid}} - F_{\substack{AquMid\\ \to TerMid}}}{F_{\substack{TerWat\\ \to AquWat}} - F_{\substack{AquWat\\ \to TerWat}} + F_{\substack{TerMid\\ \to AquMid}} - F_{\substack{AquMid\\ \to TerMid}} + F_{\substack{TerWat\\ \to Downstream}} + F_{\substack{TerMid\\ \to Downstream}}} . \\ &= 0.33 \end{aligned} \tag{15}$$

This differs from the stated SKB parameterisation (from Löfgren) which is

$$
\begin{aligned}
& Ter\_adv\_mid\_up\_norm\Big|_{Löfgren,(2015)} \\
&= \frac{F_{\substack{TerMId \\ \to TerWat}} + F_{\substack{TerMId \\ \to AquMid}} + F_{\substack{TerMId \\ \to TerLow}} - F_{\substack{TerWat \\ \to TerMid}} - F_{\substack{AquMid \\ \to TerMId}}}{F_{\substack{TerWat \\ \to Downstream}} + F_{\substack{TerMid \\ \to Downstream}}}, \\
&= 0.30
\end{aligned}
\tag{16}
$$

a small disparity.

4. $Aqu\_adv\_mid\_up\_norm$ **- flow in the aquatic mid-regolith**

   Once more scaled to the total flux captured in the catchment, this parameter is obtained by combining Equations (5a), (7) and (13):

$$
\begin{aligned}
& Aqu\_adv\_mid\_up\_norm \\
&= \frac{F_{\substack{AquMid \\ \to AquWat}} + F_{\substack{AquMid \\ \to TerMid}}}{F_{\substack{TerWat \\ \to AquWat}} - F_{\substack{AquWat \\ \to TerWat}} + F_{\substack{TerMid \\ \to AquMid}} - F_{\substack{AquMid \\ \to TerMid}} + F_{\substack{TerWat \\ \to Downstream}} + F_{\substack{TerMid \\ \to Downstream}}}. \\
&= 0.70
\end{aligned}
\tag{17}
$$

and the parameterisation as used in the SR-Site dose assessment model gives

$$
\begin{aligned}
& Aqu\_adv\_mid\_up\_norm\Big|_{Löfgren,(2015)} \\
&= \frac{F_{\substack{TerMId \\ \to AquMid}} + F_{\substack{AquWat \\ \to AquMid}}}{F_{\substack{TerWat \\ \to Downstream}} + F_{\substack{TerMid \\ \to Downstream}}}. \\
&= 0.64
\end{aligned}
\tag{18}
$$

As with the terrestrial normalisation factor, there is a small numerical discrepancy

Because the runoff is specified as 186 mm year^{-1} (p345 of Löfgren 2010) this allows the areal ratio in Equation (12) to be determined. Similarly the flux downstream from the lake (in Table 1) defines the ratio of the total watershed – though it is not clear why it is necessary to distinguish the total catchment from the total watershed in SKB's description. In this way there are as many as three distinct ways of obtaining the numerical parameters in the SR-Site RNT model, the numerical values in SKB (2015a) and the original data in Löfgren (2010). These are summarised in Table 2.

Overall there are no major differences between the three methods. The partitioning of the flux from the lower regolith is straightforward and the same in each interpretation. There are, however, some notable differences. The flooding coefficient derived here, and as quoted by SKB (2015a) is similar. The value in the original Löfgren description is rather lower. Similarly there are small differences between the values obtained for the scaling factors for the flow in the mid-regolith. Given the concerns expressed about the determination of the water fluxes in Equations (3) and (5), this further casts doubt on the rigour with which the RNT model has been defined.

The derived value of the flooding coefficient (Eqn. 13) means that the value of the meteorological flux in the catchment can be found (from the 2nd expression in Table 1). The ratio of the catchment to object areas can be written as

Table 2. Comparison of numerical data derived from the analysis here, the RFI response (SKB, 2015a) and the original RNT model data description (Löfgren, 2010).

parameter	Derived here	SKB (2015a)	Löfgren (2010)
adv_low_mid [mm year^{-1}]	44	44	44
f_{flood} [-]	1.51	1.50	1.3
$fract_{mire}$ [-]	0.98	0.98	0.98
$Ter\_adv\_mid\_up\_norm$ [-]	0.33	0.30	0.31
$Aqu\_adv\_mid\_up\_norm$ [-]	0.70	0.64	0.64
$\frac{area_{catch}}{area_{obj}}$ [-]	4.87	4.90	5.66
$\frac{area_{watershed}}{area_{obj}}$ [-]	5.32	5.32	5.32
$\frac{area_{watershed}}{area_{catch}}$ [-]	1.09	1.09	0.94

$$\frac{area_{catch}}{area_{obj}} = \frac{\Phi_{\substack{AquWat \\ \rightarrow TerUp}}}{f_{flood} * runoff} = \frac{F_{\substack{AquWat \\ \rightarrow TerWat}} + F_{\substack{AquMid \\ \rightarrow TerMid}}}{f_{flood} * runoff} \equiv \frac{1366}{f_{flood} * 186},$$

so that $\frac{area_{catch}}{area_{obj}} = 4.871$ with the derived value of f_{flood} here; $\frac{area_{catch}}{area_{obj}} = 4.896$ with the value of f_{flood} in Table 1 or 5.661 with the value of f_{flood} from Löfgren.

Similarly ratios of other areas can be determined from the parameterisation of the "*average object*" (see Table 2).

There is reasonable agreement between the analysis carried out above and the implied ratio from SKB (2015a), both agreeing that the catchment is around 4.9 times bigger than the object. The ratio is nearer 5.7 using the original Löfgren data. This appears to arise because of the way in which the total flow out of the object is evaluated by Löfgren. Kłos *et al*. (2014) have already noted that the ratio is fixed in this approach and it is not clear that the other objects in the landscape will confirm to this assumption. Furthermore, this ratio might well occur only for a snapshot of the configuration of the object and catchment during the evolution of the basin. Again, the reliability of the approach taken by SKB is to be questioned. The numerical implications are investigated in Section 3, below.

Overall the description of the translation from the details of the MIKE-SHE modelling via the "average object" to the RNT model has suffered from a lack of attention to detail during the modelling stage and a lack of adequate documentation in the main reports. The RFI has not remedied this. Nevertheless there is reasonable convergence between the numerical values derived in different ways. The main caveat is that the parameterisation, with these numerical values, is only suitable for a basin with $\frac{area_{catch}}{area_{obj}} \approx 5$.

2.4. Discussion

The Reference Biospheres Methodology (IAEA, 2003) sets guidelines for the definition of models fit for the purposes set out in the regulatory and site contexts. Key steps in the process are "system identification and justification".

SKB's definition of the SR-Site radionuclide transport model (an essential component in the dose assessment modelling) uses MIKE-SHE to characterise water flows in the surface system – this *identifies* water fluxes in the biosphere system. Moreover, use of MIKE-SHE, linked to detailed site descriptive modelling, provides a quantitative description. It is impractical to use MIKE-SHE directly in the RNT modelling. Instead the results are interpreted to fit the RNT model. The translation of the conceptual understanding provided by MIKE-SHE into the structure of the RNT model therefore requires detailed *justification*.

There is no justification for the structure of the RNT model in any of the SR-Site documentation, including the response to the RFI. The documentation implies that the RNT model was identified independently of the MIKE-SHE modelling, with only a superficial description of how the flow system for the "average object" was used to populate the database for the RNT model. The structures of the two versions of water fluxes are rather different (Figure 1 and Figure 2) and it is difficult to reconcile them (Section 2.2, above).

One area of concern is that the RNT model simplifies exchanges between compartments in terms of a net flux. This means that there is a net upwards flux of water in, for example, the exchange between the lower and mid-regolith compartments of the terrestrial sub-system (43 mm year^{-1}). However, there is flux of 60 mm year^{-1} with a return of 17 mm year^{-1}. The net flow of water is the same but the mixing of contaminants may not be adequately represented in by a single net flux, with potential errors if compartmental k_ds differ significantly..

While the use of net fluxes is understandable in the translation of Figure 1 into Figure 2 the same approach is not used to characterise the flows involving the mid-regolith. The numerical value for the flux from TerMid to TerUp cannot be understood. It is quoted as a combination of some (but not all) fluxes into and out of the terrestrial mid-regolith of the "average object". It is clearly not a "net flux" from the mid-regolith to anywhere else and the justification for combining fluxes in this way is not stated in the available documentation. Similarly the net flow from the aquatic mid-regolith to the lake is based on a selective net flux involving exchanges between the terrestrial and aquatic mid-regolith compartments of the MIKE-SHE model, despite the fact that there is no exchange between these compartments in the RNT model.

Analysis in Section 2.2 suggests that SKB dissociate the lateral flows in the three-layer “average object”. This would explain why interaction with the lower regolith is not included in the definition of the upwards fluxes in the mid-regolith. The mid- and upper regolith parts of the terrestrial and aquatic subsystems are then combined (according to obscure rules) in the definition of parameters relating to the fluxes between the terrestrial upper and lake water compartments of the RNT model as well as losses from the entire system by drainage.

For these reasons it is clear that the RNT model is not sufficiently well *justified*. The implications for the transport and accumulation of the differences between the “average object” and the RNT model are further considered in Section 3 below.

The generalisation of the fluxes in the RNT model is an essential step in defining a model that can be applied to other basins in the landscape. (Kłos, 2015a has commented on the suitability of that feature of the SR-site dose assessment modelling.) As with the interpretation of the “average object” flow system, the way in which this was done lacks transparency.

There is no *justification* for the parameterisation quoted here in Table 1 (reproduced from SKB, 2015a); the expressions are simply stated. As noted above, there seems to be a distinction between the flow system in the lower and the mid-upper regolith. In the lower regolith the fluxes are represented by a simple advective flux, so that the volumetric water flux out of the lower regolith is $adv\_low\_mid * A_{obj}$ m^3 year^{-1} where, implicitly, the volumetric flux scales with the area of the object and are independent of the size of the catchment.

Water fluxes associated with the mid-regolith use the normalised runoff to determine the advective fluxes in terms of the total water captured by the basin, for example the upwards volumetric flux from the terrestrial mid-regolith to the upper regolith is $Ter\_adv\_mid\_up\_norm * area_{catch} * runoff$ m^3 year.

Flow in the lower regolith is therefore treated differently from flow in the mid and upper regolith. Kłos *et al*. (2014) have already noted the “snapshot” nature of the model imposed (without discussion) by SKB, in that the areas of the catchment and object are fixed for all stages of the evolution to be representative of the “average object” at 5000 CE, the time at which flows in the “average object” are defined. The differences expressed in Table 2 between the numerical values used to define the RNT model parameters further illustrate the lack of transparency in the definition of the RNT.

The following section of this reports investigates the implications for the concentration of radionuclides in the RNT model.

3. Numerical implications

3.1. Alternative model for lake-mire

Kłos (2015a) has defined an alternative, evolving basin-scale transport model as part of a dose assessment model that has been used to compare results from SR-Site (Kłos, *et al*., 2015). That model looked, in part, at alternative interpretations of the overall flow system of the regolith in the whole basin. Results indicate that doses (specifically Landscape Dose Factors – LDFs) calculated by SKB were reasonable and that there were no obvious discrepancies that would lead to higher consequences. Overall the uncertainty in results calculated by Kłos *et al*. (2015a) was better quantified and more closely linked to the features, events and processes (FEPs) in the basin.

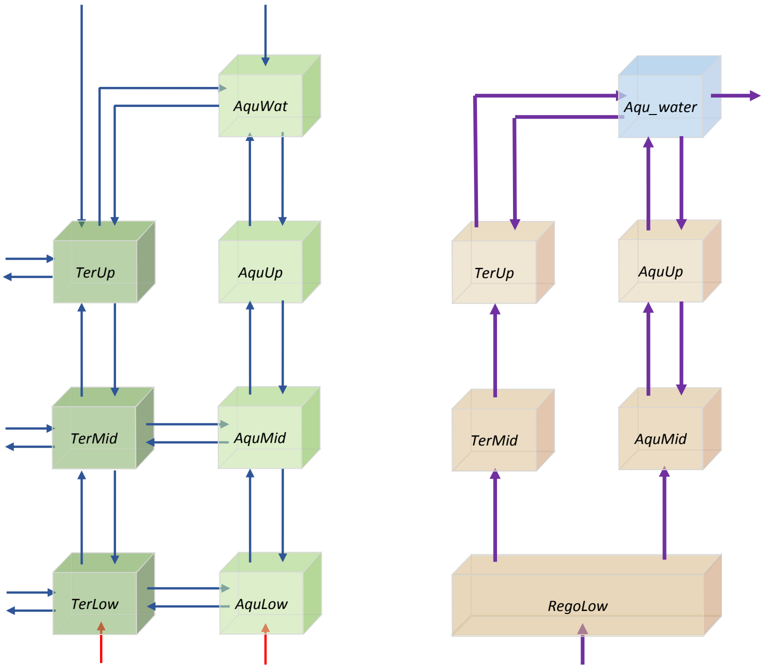
The radionuclide transport model (the RNT model, below) described by Avila *et al*. (2010) is an approximation of the flow system of the “average object”. It is a set of algebraic relations that are intended to represent a range of potential objects in the landscape. The flow system in the “average object” can be used directly to form a radionuclide transport model that exactly represents transport and accumulation in the “average object” - this is referred to as the AVO RNT model. It is therefore possible to compare the distribution of radionuclides in each of the two models of the “average object”. This comparison illustrates how representative is the Avila *et al*. RNT model.

Furthermore, the flux maps for the specific lakes used to define the “average object” (see Appendix 2) can also be used to form specific RNT models (based on the AVO RNT model but with modified fluxes). The Avila *et al.* RNT can be used to model these (since the RNT is designed to represent a wide range of objects). Comparisons of results from the object specific AVO RNT model with the RNT model indicate how well the Avila approach matches the distribution of radionuclides using the exact flow systems shown in Appendix 2.

3.2. Model definition

3.2.1. Dataset and structures

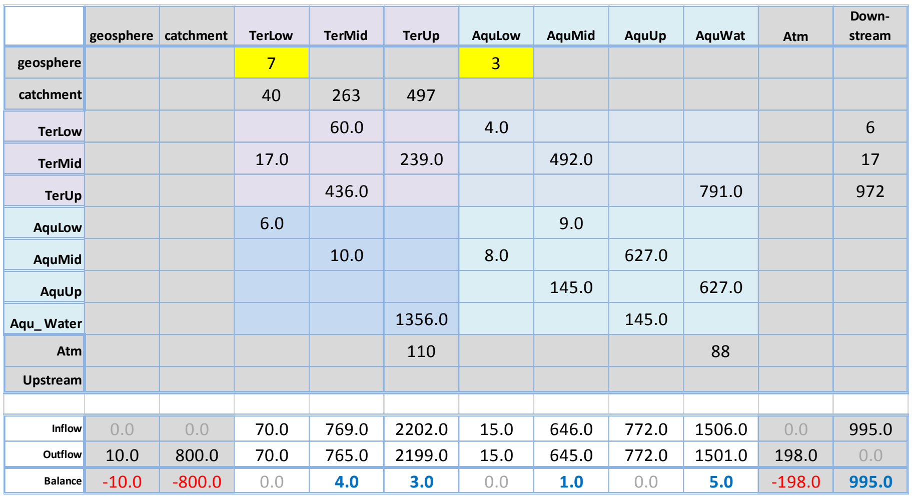
The models applied here are non-evolving radionuclide transport models of the lake mire system. All model data and parameters are kept constant, only the radionuclide inventories in the model compartments change in time. The source term for radionuclides is assumed to be 1 Bq year^{-1} of each of ^{79}Se, ^{94}Nb, ^{129}I and ^{226}Ra (with ingrowth of daughters ^{210}Pb and ^{210}Po). The models are run to equilibrium, usually after 10 kyear but before 100 kyear.



Modified “average object” transport model – **The AVO RNT model**, exact implementation of numerical fluxes for specific objects.

Fluxes in the Avila *et al*. (2010) radionuclide transport model – **The AVO model**, an algebraic simplification of the “average object” flow network.

Figure 4. Model structures for the numerical comparison of radionuclide transport and accumulation. These model structures are implemented in Ecolego to simulate radionuclide transport and accumulation. They are based on the structures shown in Figure 1 (for the “average object”) and Figure 2 (RNT model), but are modified to include common compartments (upper regolith in each model). This requires reinterpretation of the “average object” TerWat compartment as TerUp. See text for details.



	geosphere	catchment	TerLow	TerMid	TerUp	AquLow	AquMid	AquUp	AquWat	Atm	Down-stream
geosphere			7			3					
catchment			40	263	497						
TerLow				60.0		4.0					6
TerMid			17.0		239.0		492.0				17
TerUp				436.0					791.0		972
AquLow			6.0				9.0				
AquMid				10.0		8.0		627.0			
AquUp							145.0		627.0		
Aqu_ Water					1356.0			145.0			
Atm					110				88		
Upstream											
Inflow	0.0	0.0	70.0	769.0	2202.0	15.0	646.0	772.0	1506.0	0.0	995.0
Outflow	10.0	800.0	70.0	765.0	2199.0	15.0	645.0	772.0	1501.0	198.0	0.0
Balance	-10.0	-800.0	0.0	**4.0**	**3.0**	0.0	**1.0**	0.0	**5.0**	-198.0	**995.0**

Figure 5. Summary of water fluxes (mm year^{-1}) in the modified “average object” transport model. Modified from Kłos *et al*. (2015b) to include the additional compartments for the transport modelling. Fluxes from geosphere are inferred from the discussion in Bosson *et al*. (2010). Rounding errors in the “average object” mean that perfect balance is not achieved. The yellow compartments define the release distribution. In this case 0.7 and 0.3 Bq year^{-1} enter terrestrial and aquatic sub-models respectively.

Table 3. Numerical parameters for the model intercomparison. For simplicity all properties of terrestrial and aquatic regolith are assumed to be the same.

	Parameters	Terrestrial	Aquatic	Comment
	A_{obj}	1.60E+05	1.4E+05	Average of six lakes used to define "average object". R-10-02
	A_{catch}/A_{obj}	4.9		Table 2 – implied
	A_{catch}	1.5E+06		Eqn (12) – implied
Lower Regolith	Thickness	1.00	1.00	Reference value cf TR-10-06
	Porosity	0.21	0.21	Glacial till, TR-10-01, p339
	Bulk density	1980	1980	Glacial till, TR-10-01, p338
	Chemistry class	inorganic	inorganic	TR-10-01
Mid-Regolith	Thickness	0.50	0.50	Assumed for modelling here
	Porosity	0.64	0.64	Post-glacial clay, TR-10-01, p339
	Bulk density	138	138	Post-glacial clay, TR-10-01, p338
	Chemistry class	inorganic	inorganic	TR-10-01
Upper Regolith	Thickness	0.50	0.50	Assumed for modelling here
	Porosity	0.89	0.89	Peat - TR-10-01 p338
	Bulk density	86.00	86.00	Bulk density of peat, R-10-01, p338
	Chemistry class	inorganic	inorganic	TR-10-01
Water	Depth	-	1.00	Assumed for modelling comparison, consistent with TR-10-01

R-10-02 – Bosson *et al*. (2010)
TR-10-01 – Löfgren (2010)
TR-10-06 – Avila *et al*. (2010)

Figures quoted are bulk density, ρ_B. Equivalent grain density, ρ, is given by $\rho_B = (1 - \varepsilon)\rho$. This uses the porosity of the material in the compartment ε.

Table 4. Radionuclide specific parameters for the model comparison. Data taken from Nordén *et al*. (2010). (K_d for lakes ecosystems also included, though not used.)

		K_d [m^3 kg^{-1}]		
nuclide	**halflife [year]**	**organic**	**inorganic**	**lake water**
^{79}Se	1.13E+06	0.53	0.022	8.4
^{94}Nb	2.03E+04	40	1.9	230
^{129}I	1.57E+07	0.71	0.0071	10
^{226}Ra	1.60E+03	2.3	7.3	7.4
^{210}Pb	2.23E+01	43	7.7	540
^{210}Po	3.79E-01	6.6	0.21	10

The RNT model can be used directly with the fluxes as described by Avila *et al*. (2010), SKB (2015a). However, because the MIKE-SHE generated "average object" does not have upper regolith compartments some reinterpretation is required to formulate the AVO RNT model, see Figure 4. A similar approach is taken as with the RNT model interpretation: the aquatic upper regolith compartment is placed between the mid and water (lake) compartments. Fluxes exchanged between AquMid and AquWat are assumed to go via AquUp. AquUp is assumed not to be in contact with the terrestrial upper regolith (TerUp) since it represents the bed sediment of the lake.

The TerUp compartment takes the place of the TerWat compartment in the "average object" scheme. The justification for this is that the upper regolith of the mire represents saturated high porosity, loosely consolidated peat (porosity is typically 89%, density is 86 kg m^{-3}; Löfgren, 2010). Naturally this changes in time as the system matures. For present purposes, then, TerWat ≡ TerUp is reasonable, and the solid content of the compartment is significantly higher than the AquWat compartment.

Thickness of the peat layer varies in the landscape (Lindborg, 2015). For reference, we take a compartment thickness of 0.5 m for the upper and mid-regolith layers. The thickness of the lower regolith is assumed to be 1 m in each of aquatic and terrestrial sub-systems. The aquatic compartments have similar properties, the difference being that there is a water column, the depth of which is taken to be 0.5 m. The mid- and lower regolith layers are assumed to be glacial clay (mid-regolith) and till (lower regolith). Radionuclide k_ds in these media are therefore distinguished as either organic (peat layers) or inorganic (clay, till). The data are collected in Table 3.

The areas of mire and lake are averages of the areas of the six lakes used to define the "average object", namely A_{ter} = 1.6E5 m^2 and A_{aqu} = 1.4E5 m^2.The area of the catchment is derived from the total object area using the estimated ratio of catchment to object in Table 2.

3.2.2. Transfer coefficients

The models here deal only in advective transport. The first order transfer coefficients are written in terms of the water flux from compartment *i* to compartment *j*, F_{ij} m^3 y^{-1} and the volume of the donor compartment – the product of thickness, (l_i m) and surface area (A_i m^2):

$$\lambda_{ij} = \frac{1}{\theta_i + (1-\varepsilon_i)\rho_i k_i} \frac{F_{ij} A_{obj}}{l_i A_i} \text{ year}^{-1}. \tag{19}$$

This expression uses the compartment's volumetric moisture content, θ_i. As all compartments in the model here are saturated, the numerical values are equal to that of the porosity, ε_i. The radionuclides' compartmental k_ds are denoted by k_i and the grain density is ρ_i. Numerical values for the radionuclides are listed in Table 4.

The factor A_{obj} m^2 comes from the normalising area used to define the advective fluxes in Figure 1. It is clear from Sections 3 and 4 of SKB (2015a) that this is the total area of the object, $A_{obj} = A_{Ter} + A_{Aqu}$ (cf. the parametrisation in Table 1). The numerical values of the fluxes discussed in Section 2.2 above must effectively be transformed to as volumetric fluxes:

AVO RNT model: $F_{ij}\left[\text{mm year}^{-1}\right] \rightarrow \frac{F_{ij} A_{obj}}{1000}\left[\text{m}^3 \text{ year}^{-1}\right]$ year^{-1},

RNT model: $\Phi_{ij}\left[\text{mm year}^{-1}\right] \rightarrow \frac{\Phi_{ij} A_{obj}}{1000}\left[\text{m}^3 \text{ year}^{-1}\right]$ year^{-1}.

3.3. Results

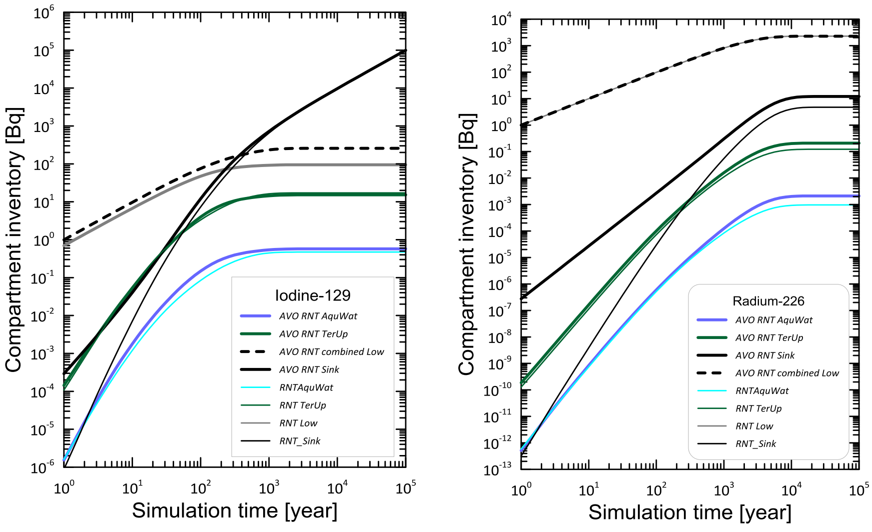
3.3.1. Overview of calculations

The questions addressed in this section of the report are:

i. Is the RNT model an adequate representation of the "average object" flow system?
ii. How does the RNT interpretation compare to results using the individual flow systems generated by MIKE-SHE and on which the "average object" is based?

This analysis does not consider whether the use of the RNT model is right or wrong, rather the intention is to examine how representative is the simplified model compared to the implementation of the exact fluxes. In this way this report provides the justification step that SKB have not addressed adequately. The analysis indicates the degree of confidence that the reviewer can have in the original Avila *et al.* (2010) RNT model. There are two stages:

i. Comparison of results from the modified AVO RNT model with those from the RNT model using the fluxes discussed in Section 2.2 for the "average object"



(a) ^{129}I (b) ^{226}Ra

Figure 6.Comparison of selected inventories for ^{129}I (weakly sorbing) and ^{226}Ra (strongly sorbing). “Average object” flow system.

ii. Comparison of the parameterised RNT model as applied to selected lakes that SKB used to generate the “average object”, using the numerical fluxes provided in response to request 2 of the original RFI (see Appendix 1).

As the models run non-evolving system the aim is to compare the distribution of radionuclides in the system over a period of 10^5 years to illustrate the implications of the two flow system interpretations. Of primary interest is the accumulation of radionuclides in the terrestrial upper regolith (TerUp) and the aquatic water column (AquWat) since it is from these two compartments that doses would be derived. The TerUp compartment is used in Avila *et al.* (2010) to define the initial concentration in agricultural soils following conversion from their natural state (as modelled using the RNT model here).

As well as the time series for compartmental inventories that are produced in the Ecolego implementation of the two models, the ratio of inventories is used as a guide to similarity; for the i^{th} compartment in the RNT model (the inventories in the terrestrial and aquatic lower regolith compartments of the AVO RNT model are summed to correspond to the single lower regolith compartment of the RNT model). The ratio is then

$$r_i = \frac{N_i(RNT)}{N_i(AVO\,RNT)}. \qquad (19)$$

for i = Low, AquMid, AquUp, TerMid, TerUp, AquWat, Sink.

With the exception of the sink inventory, $r_i > 1$ means that the SKB model is conservative. For the sink compartment the opposite is true since $r_{sink} < 1$ means that more activity is retained in the RNT compartments than in the AVO RNT model.

3.3.2. Model of the “average object” flow system.

At first sight (Figure 6), the agreement between the AquWat, TerUp and Low and Sink compartment inventories appears to be good. For ^{129}I, with relatively weak sorption, the biggest difference is seen between the lower regolith content. This is influenced by the two distinct lower regolith compartments in the AVO RNT model. At earlier times the loss from the system slightly greater but this is resolved beyond a few hundred years, when equilibrium in the system is established. For ^{226}Ra the lower regolith content is identical – a function of retention – but there are clear, though small, differences in the water and upper regolith compartments. The AVO RNT model loses a greater quantity of activity downstream.

The surprise is not that there are some differences, it is that the results are so similar given the differences in the model structures seen in Figure 4. The plots of the inventory ratios in Figure 7 help to explain these results.

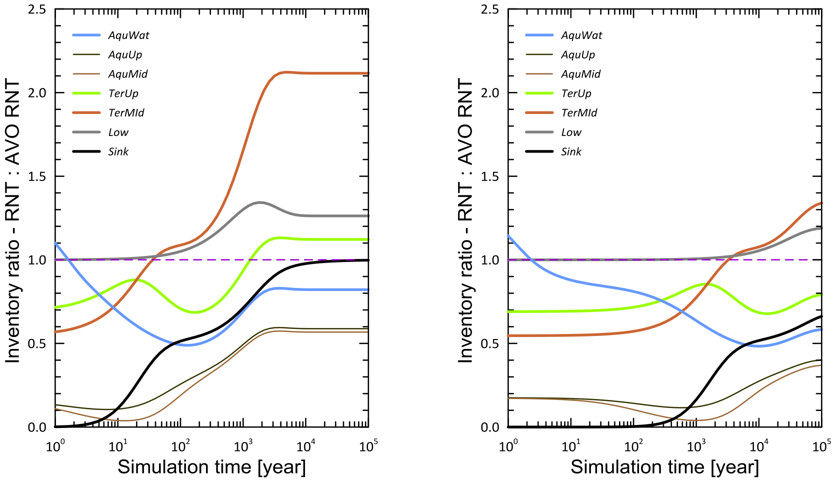
The six radionuclides shown in Figure 7 illustrate the role played by sorption and ingrowth. With relatively low k_ds both ^{79}Se and ^{129}I show similar responses. For the more strongly sorbing ^{94}Nb and ^{226}Ra there are again similarities. ^{210}Pb and ^{210}Po grow from the released ^{226}Ra. They too have relatively high sorption. Results for these three members of the ^{226}Ra decay chain are broadly similar and secular equilibrium is established fairly rapidly.

Overall these results support what was seen in Figure 6, namely that the AVO RNT and RNT models are in reasonable agreement. The value of r_i = 1 is shown and the lower k_d nuclides are close to this throughout, sometimes higher (RNT is conservative) sometimes lower. For the higher k_d nuclides the RNT is always non-conservative for TerUp inventories but the effect is small. In fact the RNT model is always non-conservative for the more sorbing species (except for AquWat at earlier times). Nevertheless it might be concluded that the RNT model is a practical representation of the flow system. The result for the TerMid compartment for ^{79}Se and ^{129}I suggests further investigation, however. Although not a high ratio (≈ 2) it is necessary to explain what is happening, especially as the flow systems appear so different in Figure 4.

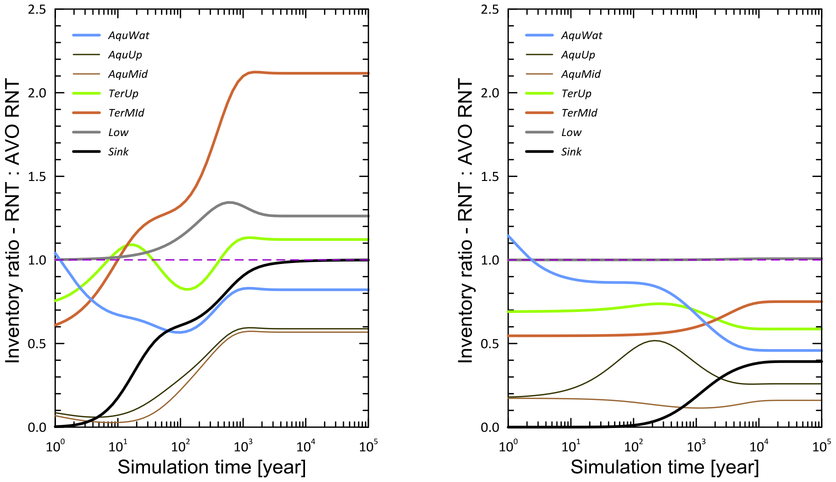
The TerUp agreement is generally good, more so for low than high k_d. An analysis of the radionuclide fluxes *into* and *out of* the TerUp compartments of the two models is shown in Figure 8 for ^{129}I and Figure 9 for ^{226}Ra.

The total input to of ^{129}I to TerUp is similar in each model (red line in Figure 8 a and b). However, how this total input is derived is different in each model. The release is predominantly to the terrestrial side and so, at earlier times, input is via the terrestrial mid regolith. For the first ten years this route dominates. Thereafter transfers via the aquatic system take over. The transition is earlier for the AVO RNT model and the final flux from TerMid is significantly lower than in the case of the RNT model. Similarly the equilibrium value of the transfer from AquWat is higher than in the case of the RNT model.

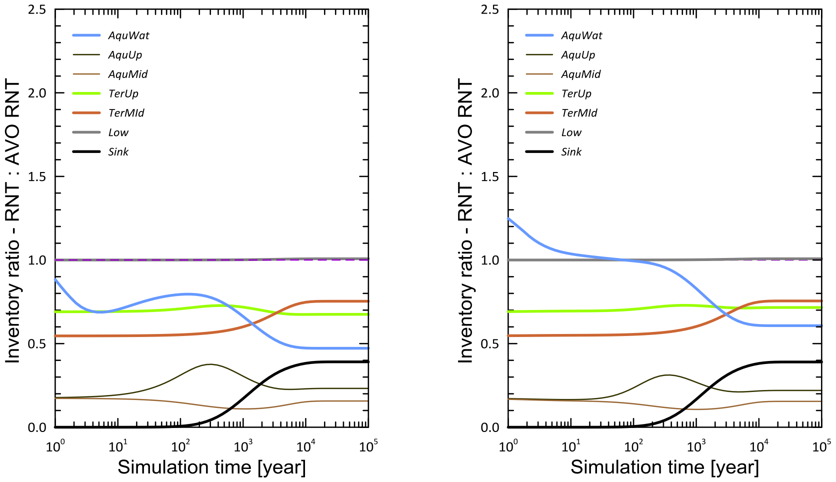
Although the overall input to the upper terrestrial regolith is close in the two models over the period of the simulation, the input via TerMid is of greater importance in the RNT model. In part this relative importance of TerMid in the RNT model stems from the accumulation in this compartment in the ratios plot, Figure 7c.



(a) ^{79}Se (b) ^{94}Nb

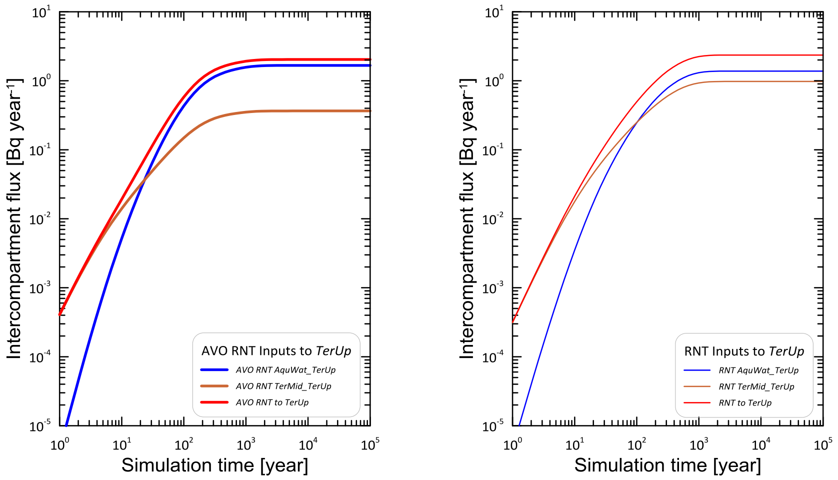


(c) ^{129}I (d) ^{226}Ra

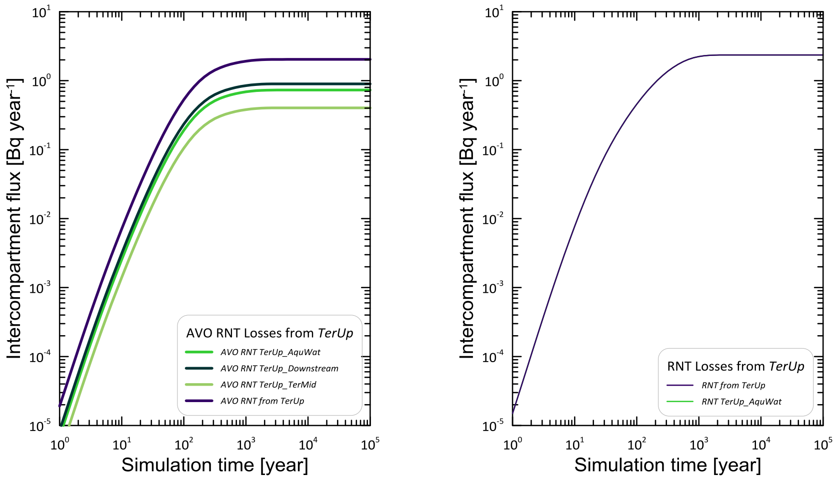


(e) ^{210}Pb (f) ^{210}Po

Figure 7. Ratios of compartment inventories – RNT model : AVO RNT model. Results for all six radionuclides in the modelled system. Agreement between the models is denoted by the dashed line at *r* = 1.



(a) AVO RNT to TerUp (b) RNT to TerUp

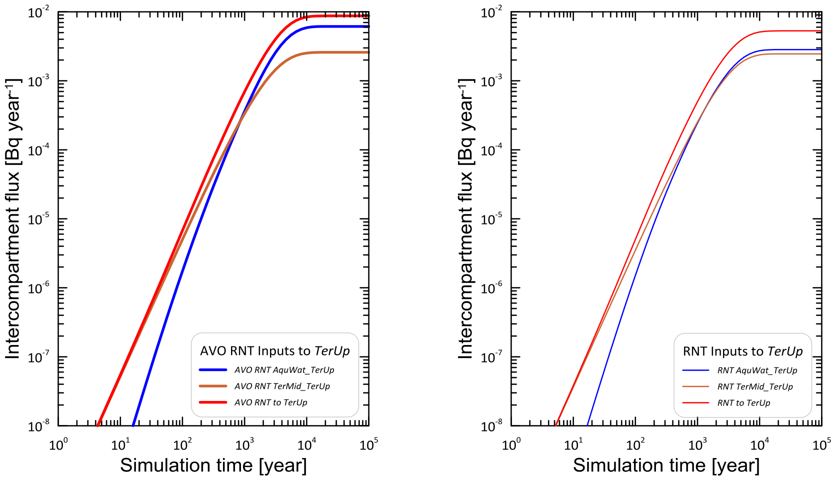


(c) AVO RNT from TerUp (d) RNT from TerUp

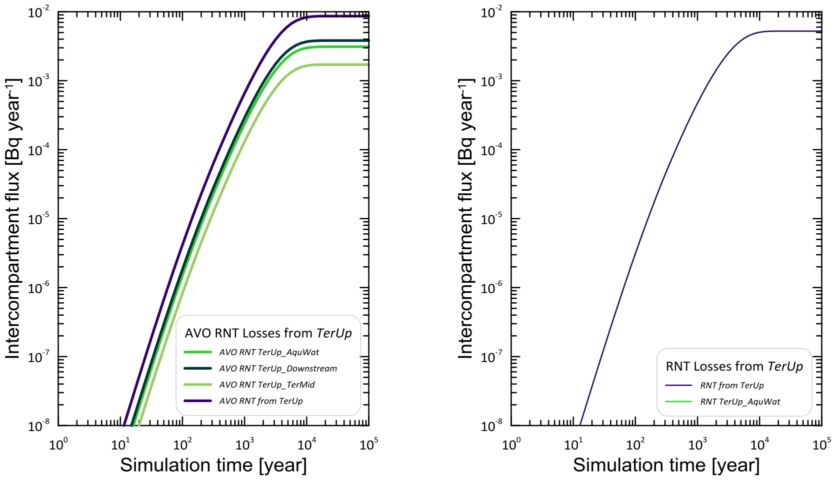
Figure 8. Comparison of ^{129}I fluxes into and out of the terrestrial upper regolith.

For ^{129}I here, flow from the lower regolith of the AVO RNT is of lesser importance. Loss from TerUp is to water in the RNT and this corresponds to the sum of all losses from in the AVO. Losses from TerUp are controlled by a single flux in the RNT model and this corresponds closely to the combined fluxes to TerMid, AquWat and Downstream. This is easier to understand. Results for ^{79}Se, also with a low k_d, are similar.

In the case of ^{226}Ra (higher k_d radionuclide) there is a greater discrepancy between the total flux into TerUp, as seen in the red lines of Figure 9a & b. The difference is less than a factor of two and, as with ^{129}I, the main source of ^{226}Ra into the upper regolith in the AVO RNT model is from the water compartment. Fluxes from the water compartment in the RNT model are lower. Both models give a similar flux from TerMid to TerUp.



(a) AVO RNT to TerUp (b) RNT to TerUp



(c) AVO RNT from TerUp (d) RNT from TerUp

Figure 9. Comparison of ^{226}Ra fluxes into and out of the terrestrial upper regolith.

In the case of ^{226}Ra (and the other higher k_d radionuclides) the overall content of the terrestrial upper compartment is lower because there is a lower input from AquWat. In turn, this is a consequence of the lower inventory in the water compartment (cf. Figure 7d for ^{226}Ra and b, e and f for the other strong sorbers. As seen for ^{129}I, input to the terrestrial sub-system dominates at earlier times and the transfer from TerMid to TerUp dominates for the first 100 years. The effect of k_d is to smooth out the differences between the models and the earlier development of fluxes into TerMid is similar over the first 1000 years.

Taking the inventory in TerUp as a benchmark, results for the “average object” (used to calibrate the RNT model) suggest that the RNT model works reasonably well; for weakly sorbing species because there is little retention in the system and thereby a higher loss from the water column, activity reaches TerUp via the TerMid compartment which shows relatively high accumulation compared to the AVO RNT model. For highly sorbing radionuclides the TerUp inventory is slightly underestimated using the RNT model compared to the full AVO RNT interpretation. This can be traced to lower activity in the RNT model's AquWat compartment and because there is less activity in the TerMid compartment.

In short the RNT interpretation of the flow system "works" even though it is very different to the modelled "average object" flow system. This finding raises the question as to whether it is this is a fortunate combination of fluxes specific to the "average object" model and the subsequent parameterisation. To check this, we now compare results using the MIKE-SHE model water balance schemes for specific objects used in the MIKE-SHE definition of the "average object".

3.3.3. AVO RNT and AVO models for specific objects.

In order to verify the fidelity of the RNT parameterisation when applied to different basins in the landscape, we consider the ratios of compartments inventories obtained from the RNT model applied to the flux maps provided by SKB in their original response to the RFI. Details in SKB (2014) were delivered in July 2014 and this formed part of the review reported by Kłos (2015a). Appendix 2 summarises the SKB (2014) response and lists the fluxes used to define the "average object" as both advective and volumetric fluxes.

For comparison we use Lake Bolundsfjärden – a large lake with a large catchment, Lake Puttan, a small lake with a small catchment and Lake Stocksjön, a small lake with a large catchment. The flow system at 5000 CE is used and data for aquatic, terrestrial and catchment are taken from Tables 8-1 and 8-3 of Bosson *et al*. (2010). These are summarised in Table 5

In this case the volumetric fluxes from MIKE-SHE are available and these can be input directly to the AVO RNT model. The RNT model data for this comparison is based on the parameterisation of the object using the fluxes stated in Table 1. Data for the RNT parameterisation are taken from Table 1. Runoff is set to 0.186 m year^{-1} (Avila *et al*., 2010).

The model comparison again uses 1 Bq year^{-1} input. as with the comparison of the model for the "average object", above, this is partitioned in the AVO RNT model according to the input fluxes at the base of the terrestrial and aquatic lower regolith compartments. The distribution is illustrated for the different lakes in Table 6.
As may be appreciated by comparing the "average object" data in Table 5 and Table 6 the "average object" that provides the calibration for RNT model is clearly somewhat different from the "real" lakes. This dataset therefore provides a significant test of the utility of the RNT parameterisation as a "one-size-fits-all" model. Figure 10 (^{129}I) and Figure 11 (^{226}Ra) compare the results for the AVO RNT and RNT models for these three lakes and the "average object" results from Figure 7.

Results in Figure 7 were plotted in a linear scale with an overall range of 0 to 2.5. Here a log-scale is used; the overall range is somewhat greater than for the "average object". As might be expected, the RNT:AVO RNT comparison yields the closest results for the "average object" itself. Results are close to one for ^{129}I, particularly for the terrestrial upper regolith. The slight non-conservative bias for ^{226}Ra is also apparent ($r_i < 1$ for all compartments except the sink).

Table 5. Area data for the three lakes used in the comparison of results from the application of the RNT and AVO RNT models. All data taken from Bosson *et al*. (2010), from indicated figures and tables.

Lake	A_{aqu} m²	A_{ter} m²	A_{obj} m²	$A_{subCatch}$ m²	$A_{watershed}$ m²
Bolundsfjärden	393600	222400	616000	8003175	8619175
Puttan	25600	65600	91200	243809	335009
Stocksjön	8000	32000	40000	2476831	2516831
Source	Table 8-1, Bosson *et al.*, (2010)			SKB (2015a)	$A_{aqu} + A_{ter} + A_{subCatch}$
“Average object”	140000	160000	300000	1500000	1.8×10^{6}
Source	Table 3			SKB (2015a)	$A_{aqu} + A_{ter} + A_{subCatch}$

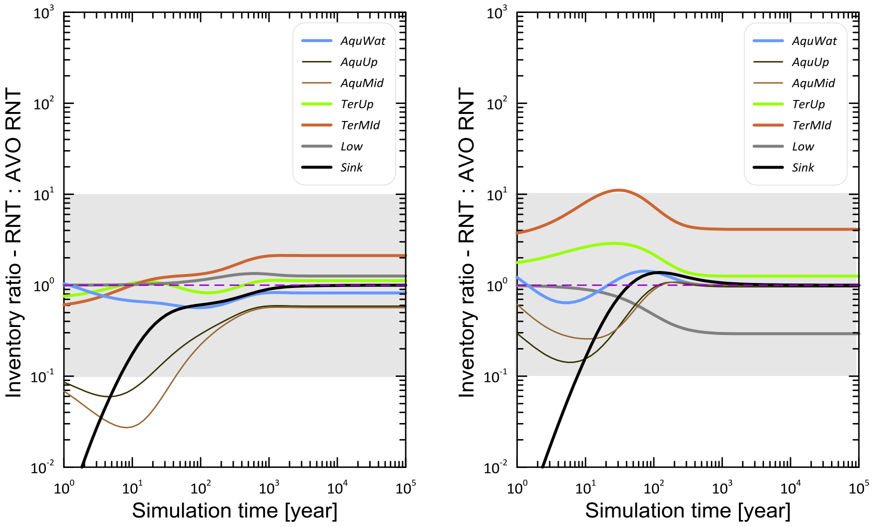
Table 6. Release flux distribution in the AVO RNT model for the lakes at 5000 CE.

Lake	Aquatic Bq year⁻¹	Terrestrial Bq year⁻¹	Total Bq year⁻¹
Bolundsfjärden	0.26	0.74	1.0
Puttan	0.00	1.00	1.0
Stocksjön	0.21	0.79	1.0
“Average object”	0.3	0.7	1.0

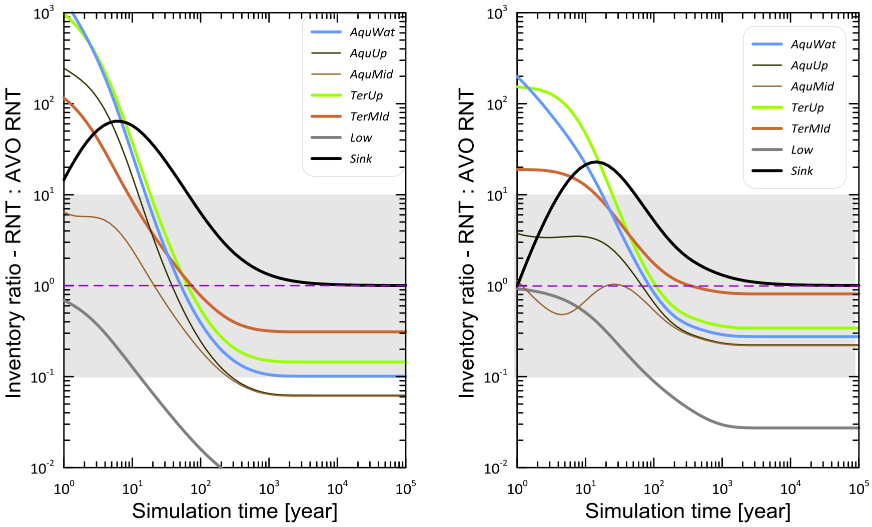
The RNT representation of Lake Puttan gives the closest “fit” to the actual hydrology. The results for ^{129}I have a slight conservative bias at earlier times but the ratio approaches one after a few hundred years, as do the other compartments except the lower regolith (non-conservative) and the terrestrial regolith (conservative). The result for TerMid reinforces the results from the “average object” model where the inventory of the was higher than anticipated. There is around a factor of ten at earlier times but this settles down to a factor of four at equilibrium. The TerMid inventory compensates for the lower than expected Lower regolith inventory. One reason for this is that there is no release to the aquatic system for Puttan at the 5000 CE snapshot used. The combination of TerLow and TerMid has a role to play in this result.

Beyond 100 years where there are significantly higher ^{226}Ra inventories in the AquMid and AquUp compartments, a feature that is accounted for by the low rates of transfer to the aquatic system using the actual Puttan hydrological map, the results are generally within the ±1 order of magnitude limits. There is again a noticeable excess in TerMid and, somewhat surprisingly, there is a small conservative bias in the results for TerUp, as there is for the lake water throughout the simulation. The sink ratio is low to start with because there is enhanced transfer to AquUp with subsequent loss from the system.

Comparing the results for Bolundsfjärden and Stocksjön for each of ^{129}I and ^{226}Ra reveals certain similarities in the dynamics of the ratios. Stocksjön, the smallest of the lakes gives the highest (conservative) results, with ratios of around 1000 at the earliest times for both ^{129}I and ^{226}Ra for each of water and TerUp. For Bolundsfjärden the corresponding values are upto a few hundred. Bolundsfjärden is the largest lake in this part of the investigation.



(a) “average object” (b) Puttan

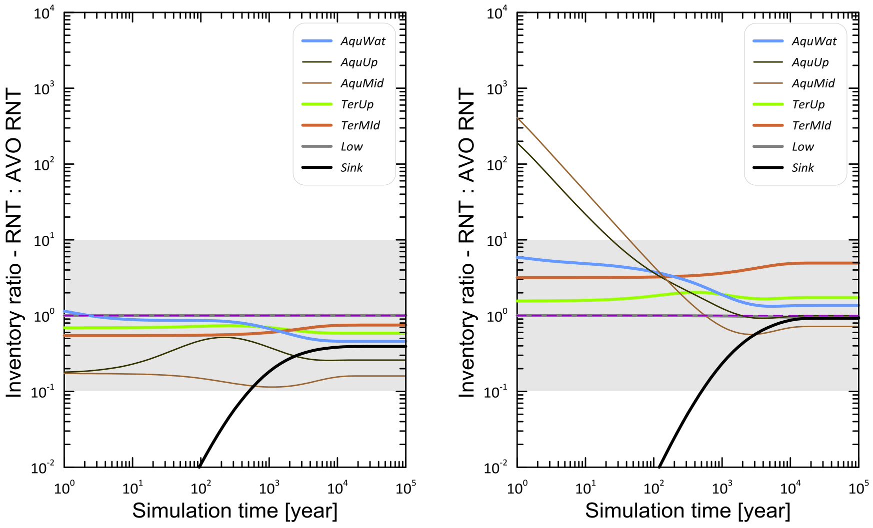


(c) Stocksjön (d) Bolundsfjärden

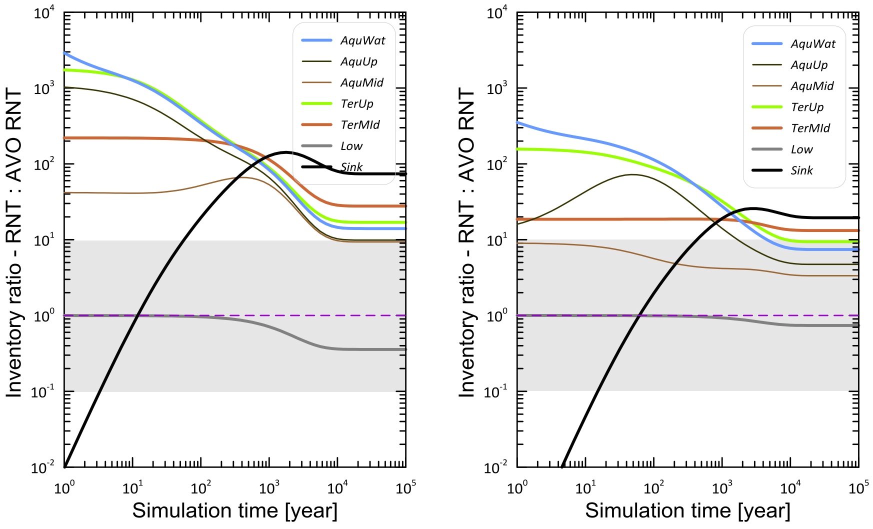
Figure 10. Comparison of ^{129}I compartment inventories for the “average object” and three lakes using the fluxes specified in Appendix 2 and those derived using the Avila *et al*. (2010) RNT model parameterisation. Shaded areas denotes ±1 order of magnitude relative to r_i = 1, that would denote equivalence between the models.

At later times there is a difference in the models’ response depending on k_d. For ^{129}I there is a small non-conservative bias after around 100 years for each lake; almost a factor of ten for Stocksjön and a factor of three for Bolundsfjärden. In contrast TerUp and AquWat inventories are higher in the RNT model at all times of this simulation, by a factor of greater than around ten.

Of the three lakes considered in this part of the review Bolundsfjärden is by far the largest. Stocksjön is only half the size of Puttan. Object size is not the only determining factor, however. The sub-catchment, as discussed in Section 2, acts to capture net infiltration (runoff). The reason that the results for Stocksjön (small) and Bolundsfjärden (large) in Figure 10 and Figure 11 have similarities is because of the



(a) "average object" (b) Puttan



(c) Stocksjön (d) Bolundsfjärden

Figure 11. Comparison of ^{226}Ra compartment inventories for the "average object" and three lakes using the fluxes specified in Appendix 2 and those derived using the Avila *et al*. (2010) RNT model parameterisation. Shaded areas denotes ±1 order of magnitude relative to r_i = 1, that would denote equivalence between the models.

influence of the focusing power. The ratio $A_{obj}/A_{subCatch}$ is 0.02 and 0.08 for Stocksjön and Bolundsfjärden respectively and 0.37 and 0.20 for Puttan and the "average object" respectively. In this sense Puttan is nearer to the "average object" than either of the other two lakes. This goes some way to explaining the difference in compartment inventory between the AVO RNT and RNT models. Furthermore, it suggests that the RNT interpretations is not a robust model of the objects in the landscape dose assessment modelling and that a distinction should have been made based on the size of the object and the size of the catchment. In short the basin as a whole needs to be considered, not just the area around the release point.

3.4. Discussion

The numerical calculations carried out here use the explicit details of the parameterisation of the object's flow system (reproduced in Table 1) that were provided by SKB (2015a). This information confirmed for the first time that the normalising area used the Avila *et al*. (2010) description to interpret the map of advective fluxes in the "average object" of Bosson *et al*. (2010) was indeed the combined area of the terrestrial and aquatic sub-models. Kłos *et al*. (2014) had already noted that the interpretation of the normalising area had implications for confidence in the SKB dose assessment modelling.

The analysis in Section 2.3 of this report shows that the "average object" in the SKB description provides a representation for objects for which the ratio of total catchment to object areas is around 5. The significance of this ratio is that it defines the diluting flow of uncontaminated water in the regolith of the biosphere system and also is a measure of the focussing power of the catchment, whereby circulating fluxes in the regolith can boost the upwards flux of water at the centre of the basin.

The modelling results in Section 3.3.1 of this report indicate that, although the Avila *et al*. interpretation of the "average object" flow system (the RNT model) is structurally very different from that of the "average object" (the AVO RNT model) the numerical results of the application of the two interpretations of the flow system produce surprisingly consistent results. In terms of the dose assessment modelling it can be concluded that the Avila *et al*. RNT model was a reasonable interpretation of the "average object" system in respect of estimates of dose calculation. For weakly sorbing the radionuclides the "fit" is better than for stronger sorbing species, for which there is a slight non-conservative bias.

Attention then turns to the suitability of the combination of "average object" and its parameterisation as a description of objects in the future landscape. Using the volumetric fluxes for three different lakes, in the dataset that was provided by SKB (2014) in the initial response to the request for further information, shows that the "average object" is not sufficiently representative of objects and basins in the landscape. The ratio of 5:1 catchment to object area is not always suitable. The results in Section 3.3.3 show that it is necessary to model different types of lakes rather than to treat all lakes, objects and basins with a single "average" model. The Avila *et al*. parameterisation of the "average object" is only good at representing the "average object". It is less satisfactory when applied to different lakes with different characteristics.

Use of the single parameterisation in Avila *et al*. is shown to be conservative by a factor of around ten for high k_d nuclides. For low k_d nuclides, however, the RNT model may underestimate the inventories in the terrestrial upper regolith (the basis for the initial distribution of radionuclides in agricultural soils) by a factor of upto ten.

These comments are based on modelling carried out using non-evolving objects. At this stage it has not been possible to investigate the implications of modelling the evolving system. What is clear from the results is that the RNT is not a good match for radionuclide transport and accumulation in different objects in the future landscape. However it is clear that LDFs in SR-Site are robust because of the conservative bias of the RNT model, since the highest LDFs come from small objects with small catchments.

4. Conclusions

This report has looked at different features of SKB's dose assessment modelling for SR-Site. The central issue is how representative of relevant landscape features events and processes is the Radionuclide Transport model (RNT model), developed by Avila *et al*. (2010) to perform the dose assessment calculations in SR-Site.

Of concern is the way in which the detailed site descriptive modelling, as embodied in the hydrological modelling using MIKE-SHE (Bosson *et al*. 2010), is used to generate a mathematical model of water fluxes that is used to drive radionuclide transport and accumulation. The model needs to be detailed enough to capture the key details of the future landscape but also simple enough to be used as a sub-model within the wider dose assessment modelling.

Material included in this review report includes the original published documentation from the SR-Site license application as well as additional material provided by SKB in response to a Request for Further Information (RFI) submitted via SSM at the end of the main review phase. The detailed analysis of the mapping of elements of the Bosson *et al*. "average object" onto elements of the RNT model shows that the procedure was not well documented, with many remaining ambiguities despite the RFI iteration. In particular the characterisation of the transfer process from terrestrial mid regolith to upper regolith is not clear and the justification is weak.

SKB's parameterisation of the fluxes in the RNT model is addressed in Section 2 of this report. We note that there is no *justification* for the approach taken; SKB's documentation comprises *identification* only; where both identification ***and*** justification are required to support model development (IAEA, 2003). Flow in the lower regolith is treated differently from that in the mid- and upper regolith. With no justification of the algebraic formulations used, it is difficult to understand why this should be so. The ambiguity in the documentation is such that the numerical values for the key parameters in the RNT model have slightly different values following the analysis carried out here, contributing to a lessening of the degree of confidence in the SR-Site model.

Earlier technical notes have raised concerns about usage of the "average object" in the radionuclide transport model employed in SR-Site (Kłos *et al*., 2014; Kłos, 2015b). The new material recently provided in SKB (2015a), together with detailed flux maps for the six lakes on which the "average object" is based, has allowed an numerical review of the implications of the use of the "average object" as the basis for the radionuclide transport model.

The numerical results confirm that SKB's parameterisation of the "average object" produces a reasonable approximation of radionuclide transport and accumulation for the "average object". When compared to flux maps for the six lakes individually, however, the results are less than convincing. Nevertheless the SKB approach is conservative for high k_d nuclides but non-conservative for low k_d species such as ^{129}I. This finding casts further doubt on the suitability of the RNT-modelling approach as applied in SR-Site

The result of this analysis further confirms that the SKB approach in SR-Site was "right for the wrong reasons", in that the calculated doses derived from the algebraic interpretation of the "average object" are similar to those that would arise if the flux maps for individual objects had been used directly despite the fact that the algebraic reformulation of the fluxes does not have the same fluxes as the “average object”. Accumulation on the key parts of the model system is determined - on longer time-scales - by the throughput of water in the compartment. In the longer term, provided the total input (from whatever compartment in the modelling network) is reasonable, the steady-state inventory will be reasonably correct. The GEMA -Site model (Kłos, 2015a), with an alternative interpretation of basin hydrology, similarly suggests that results from the SR-Site DAM are not inappropriate.

5. References

Avila R, Ekström P-A, Åstrand P-G, 2010. Landscape dose conversion factors used in the safety assessment SR-Site. SKB TR-10-06, Svensk Kärnbränslehantering AB.

Bosson E, Sassner M., Sabel U, Gustafsson L-G, 2010. Modelling of present and future hydrology and solute transport at Forsmark. SR-Site Biosphere. SKB R-10-02, Svensk Kärnbränslehantering AB.

IAEA, 2003. "Reference Biospheres" for Solid Radioactive Waste Disposal. Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, International Atomic Energy Agency report IAEA-BIOMASS-6.

IAEA, 2012. EMRAS II Environmental Change in Post-Closure Safety Assessment of Solid Radioactive Waste Repositories. Draft report of WG3, "Reference Models for Waste Disposal", working material dated (August 2012) submitted to IAEA for publication.

Kłos RA, Limer, L, Shaw, G and Wörman, A, 2014. Modelling comparison of alternative biosphere models with LDF models and evaluation of selected parameter values used in the biosphere dose assessment, SR-Site Main-Phase Review. SSM Technical Note 2014:35. SSM, Stockholm

Kłos, RA, 2015a. Model description and test: GEMA-Site 1.0. Research Report SSM 2015:47, Strålsäkerhets Myndigheten, Stockholm, Sweden.

Kłos, RA, 2015b. Main phase review - Further modelling and sensitivity study using the GEMA-Site "alternative biosphere models" and review of material from SKB's RFI response. SSM Technical Note, 2015:22. SSM, Stockholm.

Kłos, RA, Pérez-Sánchez, D, Xu, S and Nordén, M. 2015. Results from post-closure dose assessment models with "alternative" levels of detail. International High-Level Radioactive Waste Management Conference, Charleston, South Carolina, USA, April 2015.

Lindborg T (ed.), 2010. Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05, Svensk Kärnbränslehantering AB.

Löfgren A (ed), 2010. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-01, Svensk Kärnbränslehantering AB.

Nordén S., Avila R., de la Cruz I., Stenberg K., Grolander S., 2010. Element-specific and constant parameters used for dose calculations in SR-Site. SKB TR-10-07, Svensk Kärnbränslehantering AB.

SKB, 2014. Svar till SSM på begäran om komplettering rörande radionuklidtransportoch dosberäkning_2. SKB DokumentID 1440564.

SKB, 2015a. Procedure for estimation of water fluxes and associated Transfer Rate Coefficients in the Pandora Model. SKB DokumentID 1479486.

SKB, 2015b. Reply to SSM question regarding homogeneous biosphere objects. SKB DokumentID 1480681.

APPENDIX 1

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:

vii) Upwards velocity out of lower regolith: *adv_low_mid*;
viii) Fraction of flow from lower regolith directed to mire: *fract_mire*;
ix) Net precipitation: *runoff*;
x) Fraction of infiltration to catchment moving laterally in terrestrial subsystem: *Ter_adv_midup_norm*
xi) Fraction of infiltration to catchment moving laterally in aquatic subsystem: *Aqu_adv_midup_norm*
xii) 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.

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

Comments

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.

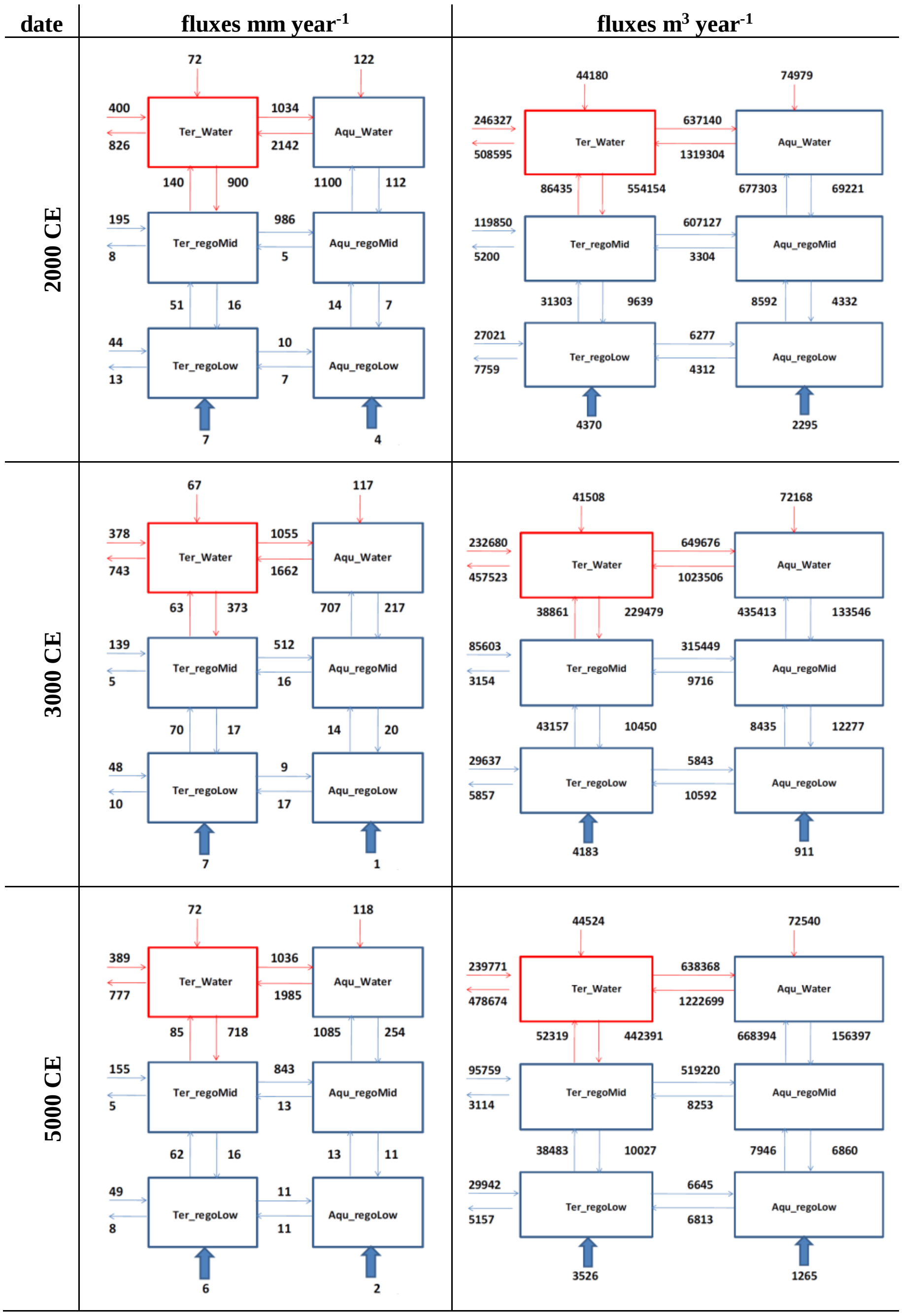
Request 2
Although the response to request 2 was quoted by SKB as being available in September of 2014, no further communication has been received. This is disappointing though not essential. The main aim of the second request was to elucidate why the radionuclide transport model in TR-10-06 (Avila *et 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.

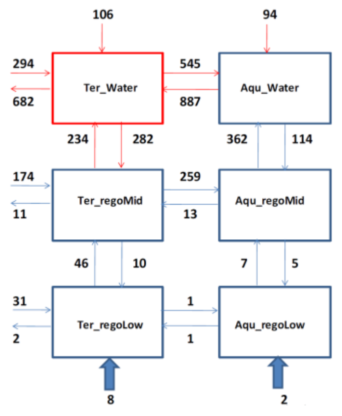
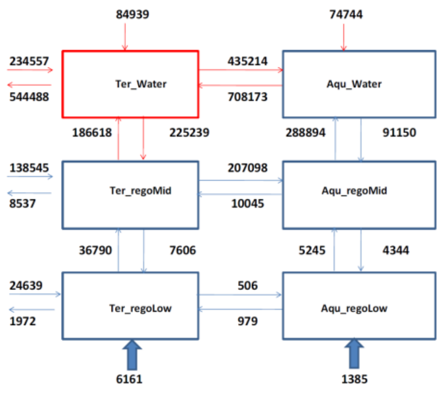
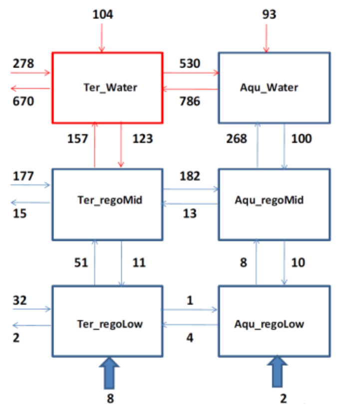
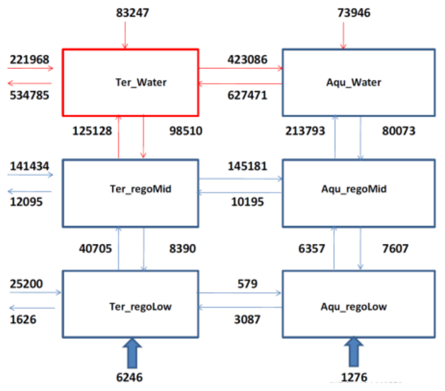
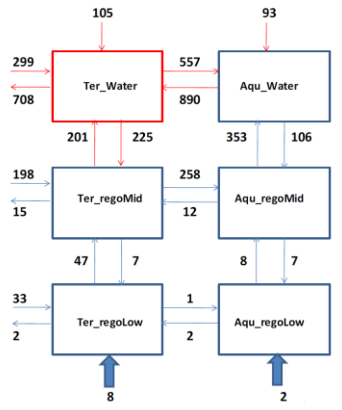
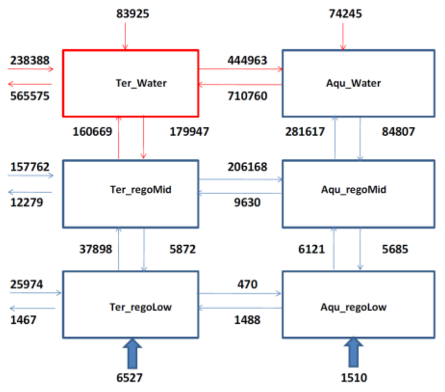
Summary of detail

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.:

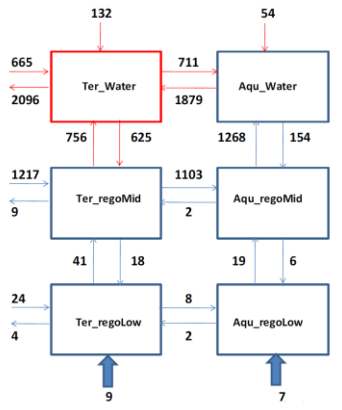
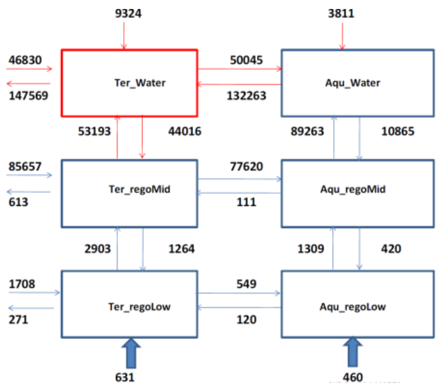
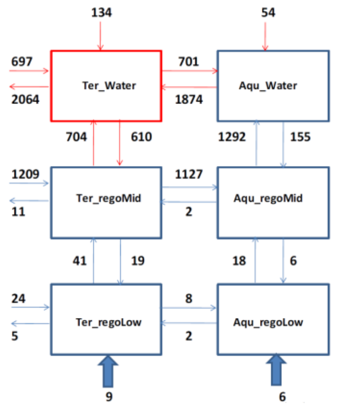
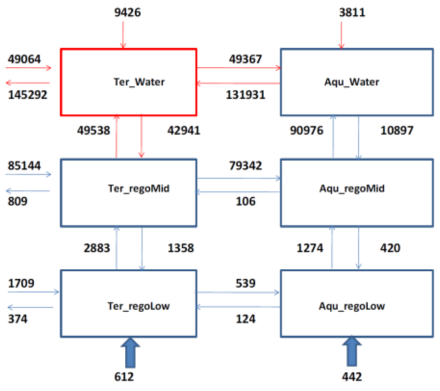
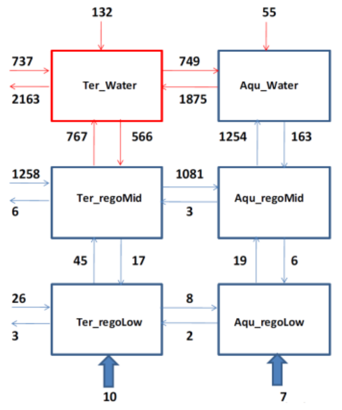
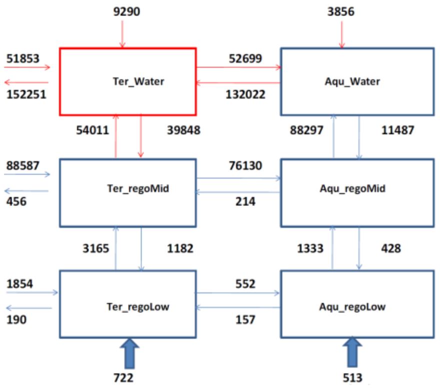
Lake Bolundsfjärden



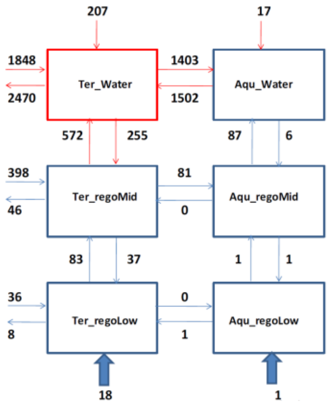
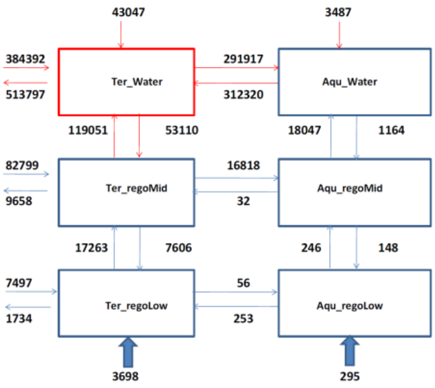
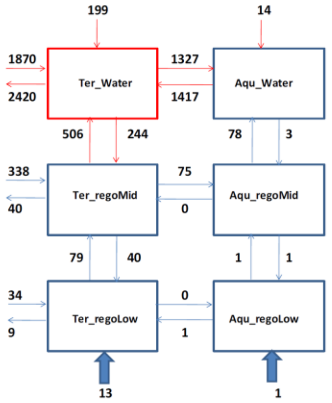
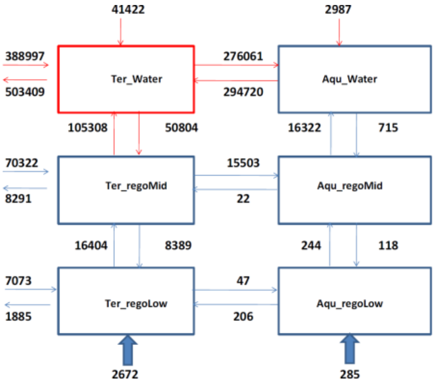
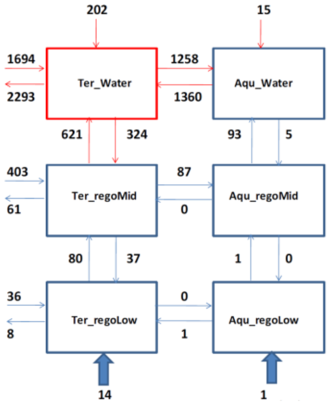
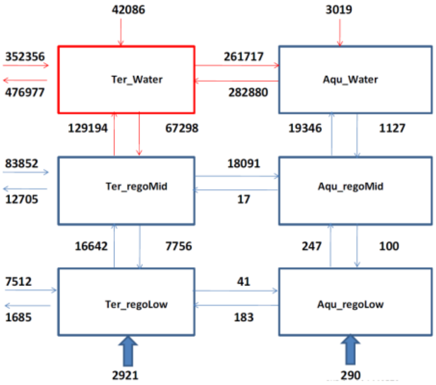
Lake Fiskarfjärden

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

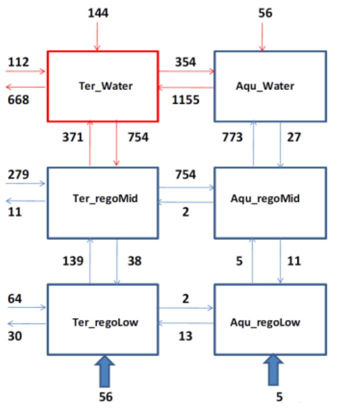
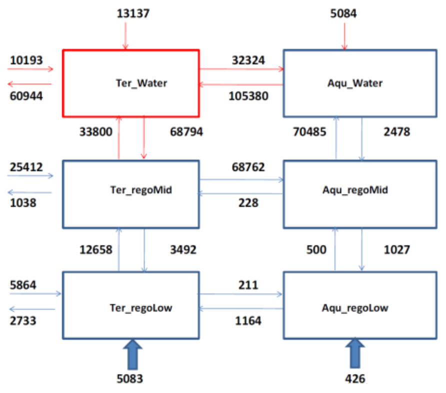
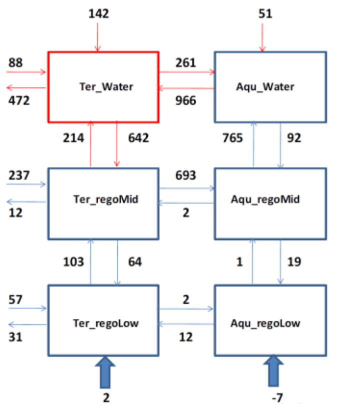
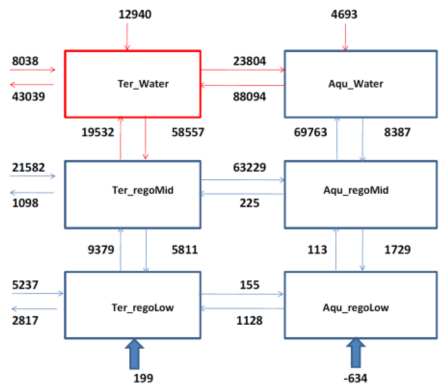
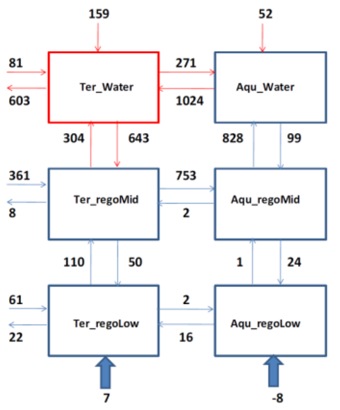
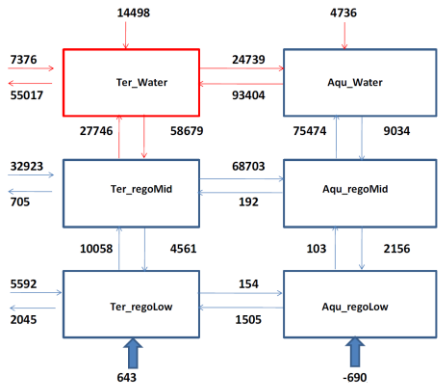
Lake Gunnarsboträsket

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

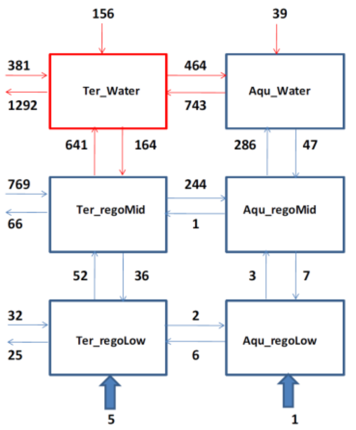
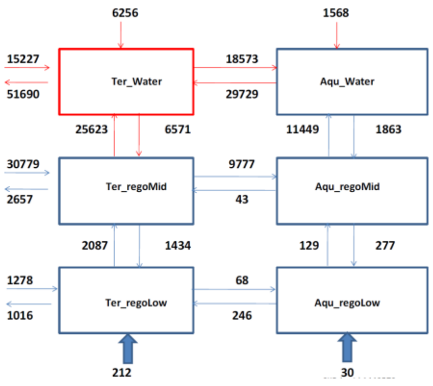
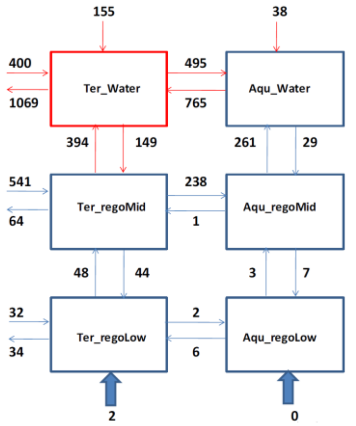
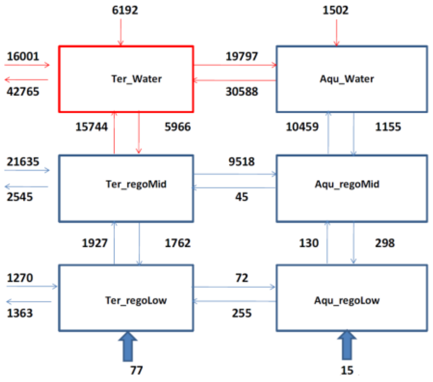
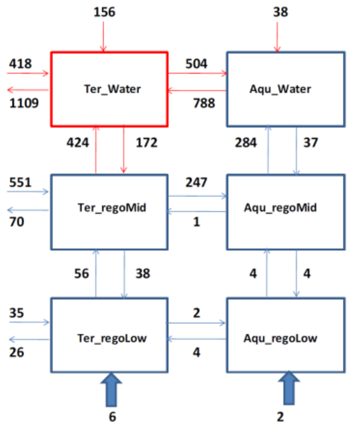
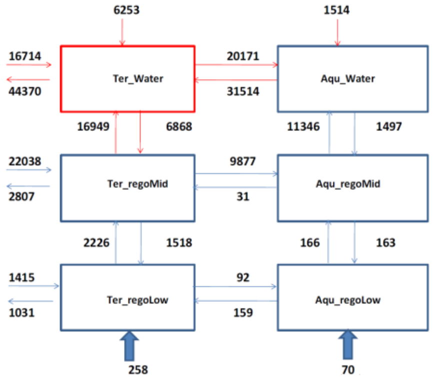
Lake Gällsboträsket

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

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		

2015:48

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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