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Reply to SSM question regarding homogeneous biosphere objects

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1 Introduction

The aim of this report is to answer the question from SSM regarding the implications of the “homogeneous contamination” of biosphere objects in the SKB model for radionuclide transport and dose calculations that was used in the SR-Site safety assessment. To this end, we present and discuss a complementary analysis of one of the SR-Site biosphere objects, and also provide a summary of some results produced within the recently published SR-PSU assessment.

In the document ”Begäran om komplettering av ansökan om slutförvaring av använt kärnbränsle och kärnavfall – Radionuklidtransport och dosberäkningar” (SSM2011-2426-103), SSM requests a complementary study based on a specification originally formulated in Swedish and translated by the authors of the present report as follows:

”SKB:s egna analyser visar att utsläppsarean i allmänhet är mycket mindre än arean av det biosfärobjekt där utsläppspunkten ligger (Lindborg, 2010, s. 168). SSM behöver en kompletterande analys av betydelsen av att biosfärobjekten antas vara homogent kontaminerade trots att utsläppspunkterna kan vara begränsade till endast en liten del av objekten, dvs. i vilken utsträckning rumslig utspädning kan förekomma.” (SKB’s own analyses show that the discharge area generally is much smaller than the biosphere object where discharge occurs (Lindborg 2010, p 168). SSM requests a complementary analysis of the significance of the fact that biosphere objects are assumed to be homogeneously contaminated even though discharge could be limited to only small parts of the objects, i.e. to what extent spatial dilution may occur.)

Thus, SSM has noticed that results from a distributed transport model in Lindborg (2010) in some cases indicate that discharge areas may be small relative to the sizes of the biosphere objects that constitute a sort of “smallest units” in the compartment-based model used in the biosphere radionuclide transport and dose calculations, and wants a complementary study of the effects of the assumption underlying the radionuclide modelling.

The present SKB response to this request is organised as follows. The next section, Section 2, provides some comments on the modelling results referred to by SSM, a discussion of processes affecting discharge areas, and a brief description of relevant parts of the SR-Site biosphere modelling. Section 3 presents a complementary study of an SR-Site object, where calculations are performed for a set of subareas within the object, Section 4 summarises a comparison between different object delineations that was performed within SR-PSU, and Section 5 presents the conclusions drawn from the previous sections.

2 Comments on SR-Site models and results

Before the presentations in Sections 3 and 4 of new/recent modelling results addressing the SSM question, this section discusses some aspects of the SR-Site results and the models used to produce them. Specifically, this part of the presentation provides comments on the results presented in Lindborg (2010) and describes some features and underlying assumptions of the SR-Site biosphere transport and dose calculations reported in Avila et al. (2010).

2.1 Discharge area calculations

Since the question asked by SSM refers to a specific set of modelling results in SR-Site, this section begins with a few comments and perhaps also clarifications regarding these results. These comments

are followed by a more general (brief) discussion of factors that could affect discharge locations and sizes of discharge areas, and what they could mean in the present context.

First, it should be acknowledged that the modelling results referred to by SSM (i.e. those discussed in page 168 of Lindborg (2010) and illustrated in the associated figures) indeed show contaminated areas that are smaller than the biosphere objects, in some calculation cases much smaller. However, as discussed in Lindborg (2010) the results also indicate that differences may be large, depending on the specific flow path/source location studied and factors such as the selected concentration limit and where (at what depth) in the regolith concentrations are observed. In the report, it is argued that it is difficult to identify a “typical pattern” based on these results. In the context of the present discussion, the only consistent pattern appears to be that only parts of the objects are contaminated.

However, when assessing the implications of these results it should be noted that they were obtained using small sources relatively close to the surface (one 40-metre cell at 40 metres below sea level) and with a low degree of dispersion in the transport model. No attempt was made to evaluate what might have been realistic values of these parameters, see Bosson et al. (2010) for more details on this modelling. Probably more important, the model simulations considered a relatively short period (65 years) and fixed boundary conditions. This means that there were no long-term changes in shoreline position or meteorological conditions that could change flow and discharge with time, thereby extending the contaminated areas.

On a slightly different note, it could be observed that several of the calculation cases in Lindborg (2010) show results where the contaminated groundwater discharges close to streams and/or is transported to streams along narrow stretches, possibly without affecting much of potential agricultural land. This type of “bypassing” through groundwater transport directly to the stream network could reduce exposure and doses significantly. However, for the present discussion it is sufficient to note that concentrated discharges also could lead to reduced exposure, depending on where they take place. As explained and motivated below (Section 2.2), this kind of detailed considerations are not included in the present biosphere modelling.

Since discharge areas associated with hypothetical future releases from a planned geological repository cannot be observed at Forsmark today, assessments involving locations and sizes of such discharge areas must rely on modelling. Models and modelling results used for these purposes are affected by uncertainties (e.g. related to uncertain input data) and limitations (e.g. numerical resolution) that are common to all modelling, and by conditions specific to the problem at hand.

Regarding uncertainties related to the bedrock hydrogeology model, differences in discharge locations between different modelling approaches and also between model realisations can be observed in the SR-Site results (Selroos and Follin 2010). These differences would translate into different discharge locations within biosphere objects. No detailed analysis of the extent to which this can be seen in the SR-Site modelling results has been performed. However, the main implication of model uncertainties is that any determination of a specific discharge location is associated with uncertainty, and that this uncertainty can be large relative to the scale of the detailed models presented in Lindborg (2010).

The release scenario associated with the particular transport modelling case is another factor of importance for the size of the contaminated area. In the context of the particle tracking calculations used to identify discharge locations in SR-Site (see Joyce et al. 2010 and Selroos and Follin 2010), this is a matter of whether only one canister position is assumed to release radionuclides, or if several canisters simultaneously contribute to radionuclide transport and hence could discharge in a given biosphere object. In SR-Site, scenarios involving both single and multiple flow paths were studied. However, the main scenario involved single flow paths, and hence no increase in discharge areas due to this effect.

Other transport process-related factors affecting the sizes of discharge areas are physical dispersion in bedrock and regolith, and flow transients. Although both factors are expected to contribute, flow transients should have the largest effects on discharge areas in the very long time perspectives of a safety assessment (see, for instance, Joyce et al. 2010, Figure 6-7). On the scale of a single biosphere object, the main implication of a changing groundwater flow field (due to shoreline displacement and other long-term changes) would be that different parts of the objects receive discharge during different periods, such that larger “apparent discharge areas” are obtained. Simulations with multiple particles from each canister positions suggest that dispersion may cause a spread in discharge of deep groundwater on the scale of a hundred (rather than a thousand) metres (Joyce et al. 2010, Figure 6-16) under stationary flow conditions. Moreover, the travel times along flow paths from a single canister position may vary with as much as one order of magnitude, suggesting that individual particle pathways may end up far from the most likely position (Liu et al. 2010, Figures 4-3 and 4-4).

It follows from the present discussion that a number of factors potentially changing the discharge area results towards larger “apparent discharge areas” can be identified. Nevertheless, it seems unlikely that simulations of the type presented in Lindborg (2010) consistently would show results where the whole biosphere objects are contaminated by radionuclide-bearing groundwater from below, at least for release scenarios involving single flow paths. This implies that the biosphere objects will be partially contaminated, but probably not quite as partially as indicated by the results commented by SSM.

In addition, there are uncertainties associated with the modelling of discharge locations that could be large relative to the scale of an object and, even more, relative to sizes of specific features within the object. This indicates that it may not be meaningful, or even impossible (and certainly impractical), to apply a modelling approach based on detailed assessment of discharge areas within individual objects. The remainder of this report will be focused on the effects of partial contamination of objects, and hence on whether such detailed assessments are necessary in a safety assessment context.

2.2 Biosphere objects and their use in modelling

2.2.1 Delineation of objects

A biosphere object is an area in the landscape that potentially, at any time during the assessment period, could receive discharge of deep groundwater associated with the repository volume (Lindborg 2010). The delineation of biosphere objects starts with an identification of basins and lakes (present and future). The argument for this approach follows from the general knowledge that low-laying areas in the landscape are possible discharge areas (e.g. Joyce et al. 2010). This implies that the whole landscape is used to describe the discharge pattern of deep groundwater. It also means that the biosphere objects are associated with specific ecosystems with homogeneous properties and potentials for human land use.

As a final step of the biosphere object identification, adjustments can be made by using hydrological simulations and particle tracking. The whole approach can be seen as a two way method, where the understanding of landscape and ecosystem processes and succession is equally important as the discharge areas for groundwater to the surface when delineating objects. However, it should be noted that the pattern of calculated discharge locations is not the main information used as a basis for delineating the objects. The objects are primarily delineated based on ecosystem considerations, and the discharge locations are used to identify which objects to include in the transport and dose modelling. One practical advantage of having the object delineation partly separated from specific release scenarios is that the delineation is more likely to match with alternative sets of discharge locations, early as well as late in the assessment period.

Several possible future Forsmark landscapes were modelled and described in SR-Site. Hydrogeological simulations (particle tracking) show which specific low-lying areas (lakes, wetlands and streams) that receive discharge from starting positions (canisters) within the repository volume, and hence should be included in the biosphere modelling (see example in Figure 2-1). Single-point information from the particle tracking was not considered in isolation. Instead, clusters of discharge points from a realisation of the hydrogeological flow-field were used to establish the general patterns of discharge in the landscape for consecutive time steps in the landscape development. This implies that clusters of particles entering the surface system were interpreted as indicators of potential recipients of deep groundwater from the repository to be used as biosphere objects in the modelling.

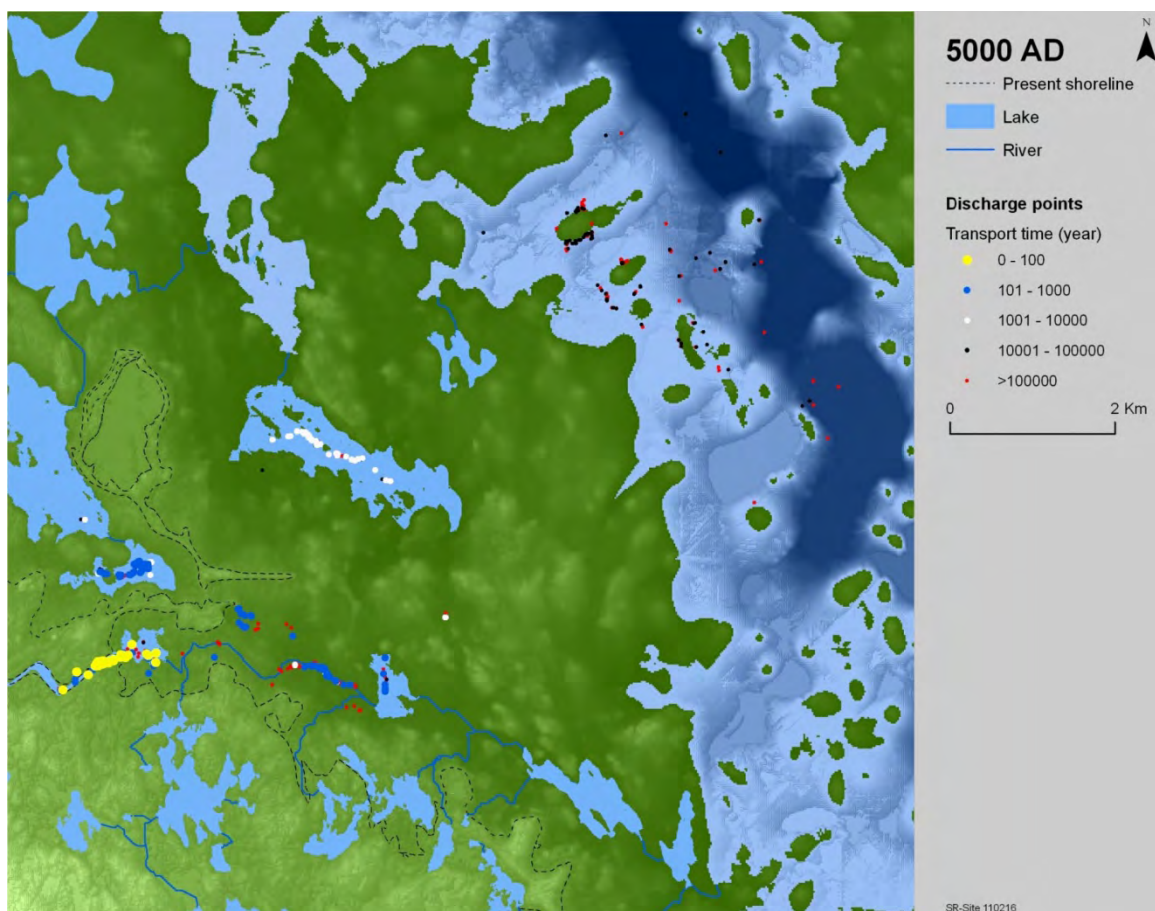


Figure 2-1. Example of discharge locations in SR-Site. The discharge locations are coloured according to advective travel times for the 5000 AD flow-field. The topography and bathymetry at 5000 AD are indicated by different shades of green and blue, respectively; darker shades correspond to lower elevations. Note that infilling of lakes has not been accounted for in the map; instead the largest extent of each lake is shown. Object 116, discussed in the text, is the large lake with many white dots in the middle of the map (figure from Lindborg (2010) based on data from Joyce et al. (2010)).

2.2.2 Use of objects in modelling

The biosphere objects were outlined in the landscape development model and parameters for the biosphere radionuclide transport and dose model were extracted for successional stages as described in

Chapter 7 of Lindborg (2010). The biosphere objects are associated with three basic geometric features (or areas): the watershed, the basin and the sub-catchment (see Chapter 7 of Lindborg (2010)). These three areas are partly overlapping, and were used to scale different processes in the biosphere radionuclide modelling (Avila et al. 2010).

The size of a biosphere object is the size of the homogeneous ecosystem (marine basin, lake, wetland and stream) in the landscape. To make sure the size (and the potential number of objects) was reasonable the present Forsmark area was used to constrain the identification of objects. Thus, the smallest existing lake with potential to support future farmlands (Lake Puttan) was used to define the lower size limit for a biosphere object also in the future landscape. No upper limit on object size was imposed. In some cases, when wetlands that never go through a lake stage were identified as potential discharge areas, the biosphere object was delimited based on future surface water/groundwater levels, as predicted by means of a hydrological model, and particle tracking information on discharge from repository depth.

The size of a biosphere object changes in time. When the object is below the sea, the whole basin is used as biosphere object. As the basin emerges from the sea, the object size changes accordingly, see Chapter 7 in Lindborg (2010). When the object turns into a lake, i.e. at the time when the bay is cut off from the sea and becomes a lake, the object size equals the lake size. After this stage, the object size is fixed but the lake/land ratio within the object will change continuously due to infilling and ingrowth of the lake, until the whole object area is land.

The delineated and parameterised biosphere objects are used to estimate doses and risks to humans and non-human biota. This task in the safety assessment has to be performed such that it produces results that are reasonable and representative of the considered site. The use of a broad set of biosphere objects allows the analysis to explore the effects of sizes and positions in the landscape on the calculated endpoints. In the end, the worst case area may be used to cautiously describe transport and accumulation in an area where deep groundwater may be discharged, and to assess the dose under different land use practices.

If only a limited part of the biosphere object is affected by radionuclide release, there will be differences in the calculated environmental concentrations and the resulting dose as compared to the case when the whole object is contaminated. Both higher and lower LDFs¹ may occur depending on size and location of the considered subarea within the original object (see Sections 3 and 4 for calculation examples). It should be noted that subdivision of objects was part of the methodology applied in SR-Site. For example, a subdivision of object 121 was found to be relevant (as two clusters of discharge points were found outside the lake basin in the terrestrial period) and all available sources of information were used to subdivide the original sea basin into subareas.

Specifically, the relatively small subarea 121_3 was handled as a separate object and was found to be extreme in terms of both object properties and endpoint results. The 121_3 object was not identified as a potential discharge area for deep groundwater in the initial steps of the assessment. In fact, it only displayed discharge area properties for some time steps under temperate conditions. Moreover, the 121_3 object is located near a water divide and has a very small upstream catchment. Thus, the 121_3 object included already in the original SR-Site calculations can be viewed as an example of a case where a biosphere object (object 121) has been divided into subareas to include the effects of a less likely release case resulting in comparatively high doses in the assessment. Other examples are shown in the following sections.

¹ The landscape dose conversion factor (LDF) is the dose obtained for a constant release rate of 1 Bq per year to the biosphere object. In the text, LDF is used for the maximum life-time dose (given a unit release rate) during the full assessment period.

2.3 The biosphere transport and dose model

The mathematical approach used in the radionuclide model of the biosphere is that of compartment modelling. It assumes that a system can be sufficiently represented by a finite number of compartments or pools, each of which is homogeneous and connected to other compartments.

In the radionuclide model used to calculate transport and doses in the biosphere, the biosphere object is subdivided into compartments, both horizontally and vertically (Figure 2-2). Each compartment represents a radionuclide inventory associated with a physical or biological component in the modelled surface ecosystems. The dynamic change of each compartment is the result of radionuclide fluxes associated with mass fluxes of water, solids (including organic matter) or gas, or with diffusion.

There are many biophysical, geochemical and physiological processes that affect transport of radionuclides in surface ecosystems, and these processes occur over a wide range of spatial and temporal scales. However, as the assessment period covers thousands of years, and the assessment areas are considered on the scale of ecosystems, compartments are represented by average conditions, and fluxes of water, solid matter and gas are described as functions of aggregated empirical parameters that are assumed to capture the outcome of the underlying processes.

The coarse spatial resolution of the compartmental structure introduces dispersion of radionuclides in the biosphere. For compartments that are well mixed by physical properties on the scale of a biosphere object, like the water of a lake or a sea basin, this dispersion is reasonable, but for regolith layers the introduced dispersion can be assumed to be larger than the real physical dispersion. With respect to vertical transport, the introduced numerical dispersion is likely to be cautious, as it will result in radionuclides reaching the surface (where humans and non-human biota may be exposed) more rapidly than in a more finely resolved model.

Horizontally, the biosphere object is represented by two columns of compartments, of which one represents the lake and the regolith below the lake and the other the terrestrial area (mire) surrounding the lake. In the model, the incoming radionuclide flux from the bedrock is directed to a common bottom layer (representing the till) and then divided into one flux that goes to the lake column and another that enters the mire column. This implies that above the till layer the object is not treated as homogeneous in the modelling. Furthermore, the relative proportions of land (mire) and lake change with time, which means that a given part of the object could belong to different ecosystems (i.e. parts of the model) at different times. However, it is true that each compartment is treated as homogenous and *if* the release is spatially restricted to parts of the object the numerically introduced dispersion can be expected to be larger than the real physical dispersion.

In the SR-Site reporting, the effects of discretisation in the radionuclide model are discussed in Section 12.3.1 of SKB (2010) and in Avila et al. (2010). Specifically, in Table 12-3 of SKB (2010) the evaluation of the quantitative effects is summarised together with the handling in the assessment. The major outcome of this exercise is that either the handling in SR-Site is cautious (as compared to alternative models) or that the effects of discretisation on endpoint results are limited (within a factor of two). Note that this considers the effect on the maximum LDF over all biosphere objects and exposure pathways, which is the focus of the assessment. Thus, while environmental concentrations in the biosphere object may be significantly affected by the discretisation, the effects on the LDF may be marginal due to for example exposure from the independent pathway from a drilled well.

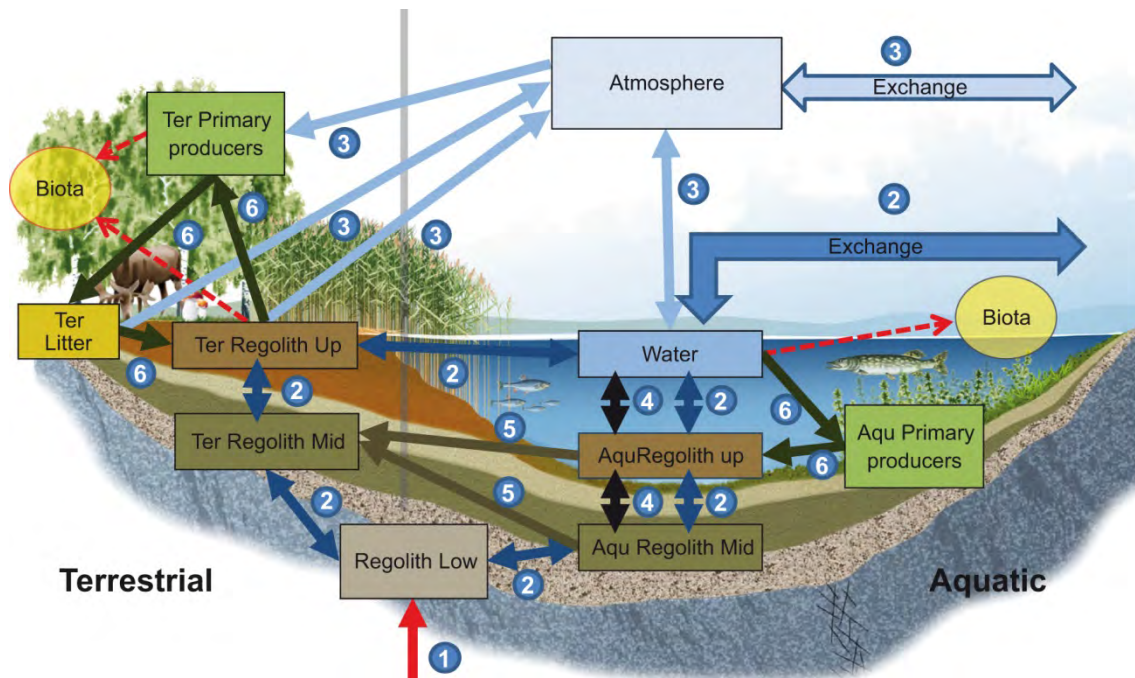


Figure 2-2. Conceptual illustration of the radionuclide transport and dose model for the biosphere. Boxes represent compartments, thick arrows fluxes, and dotted arrows concentration computations for biota (these are not included in the mass balance calculations). The model represents one biosphere object that contains an aquatic (lake, right) and a terrestrial part (mire, left) with a common lower regolith and atmosphere. The release from the geosphere is represented by a red arrow (1). A detailed description of the model is given in Avila et al. (2010).

3 Complementary study of an SR-Site object

This section describes a complementary study of one of the biosphere objects in SR-Site (object 116), where a set of “subareas” are identified and studied in model calculations. This implies that only parts of the original object area are assumed to be contaminated by the groundwater entering from below, and that the effects on LDFs of considering these hypothetical “subareas” instead of the original object are quantified.

3.1 Calculation cases

As explained above, a biosphere object is an area in the landscape that potentially could receive discharge of deep groundwater associated with the repository volume. To illustrate the effect of varying the object size and location, object 116 was subdivided in different ways, and the release of deep groundwater was assumed to occur only in these subareas. In most cases, this meant that smaller contaminated areas and smaller sub-catchment areas were investigated in the variant cases.

If only a part of the biosphere object is affected by radionuclide release from the repository and this part of the object is utilised by humans, the effects on dose can be quantified by changing the geometrical parameters representing the area in the dose calculations. Figure 3-1 illustrates three different calculation cases, with the subarea marked in blue and the associated sub-catchment (or watershed) delimited by a thick solid line. The rest of the original biosphere object 116 is indicated by the grey areas. The three variant cases considered in the analysis were: 1) only the upper part of object 116 is assumed to be affected by radionuclide release, 2) the midpoint of the object is used to delimit the areas used in dose calculations, and 3) a small area sufficient to support one family through modern agriculture close to the outlet is considered. Note that the small object in case three has the same sub-catchment area as the original object.

For each of the three alternatively delineated areas, unit release rates (1 Bq y^{-1}) of Ra-226 and I-129 from the bedrock to the lowest regolith layer (RegoLow) were used to simulate transport and accumulation for an interglacial period with temperate conditions given the extended global warming climate case. According to the reference glacial cycle used for Forsmark in SR-Site, this period starts with the deglaciation around 9000 BC and prevails until the onset of the next glaciation around 60,000 AD. Doses from the unit release were calculated assuming that the most exposed group exclusively relies on the contaminated area for food production and water resources if this area is sufficiently large to support the group. During periods when agriculture is not possible, hunters and gatherers rely on the natural landscape for food production. As the productivity of natural food is relatively low, a larger area is needed to support a band of foragers. It is unlikely that such a community will always exploit the same object over a lifetime.

As the calculations aimed to illustrate how a release of radionuclides to a part of a biosphere object affected dose from land use, exposure from a well in the bedrock was excluded from the calculations. The simulations of Ra-226 included two progeny radionuclides (Pb-210 and Po-210). Finally, the simulations were repeated for a wide range of combinations of object and sub-catchment areas spanning from half the smallest to twice the largest object and sub-catchment areas observed in the original set of SR-Site biosphere objects (SKB 2010, Figure 12-4).

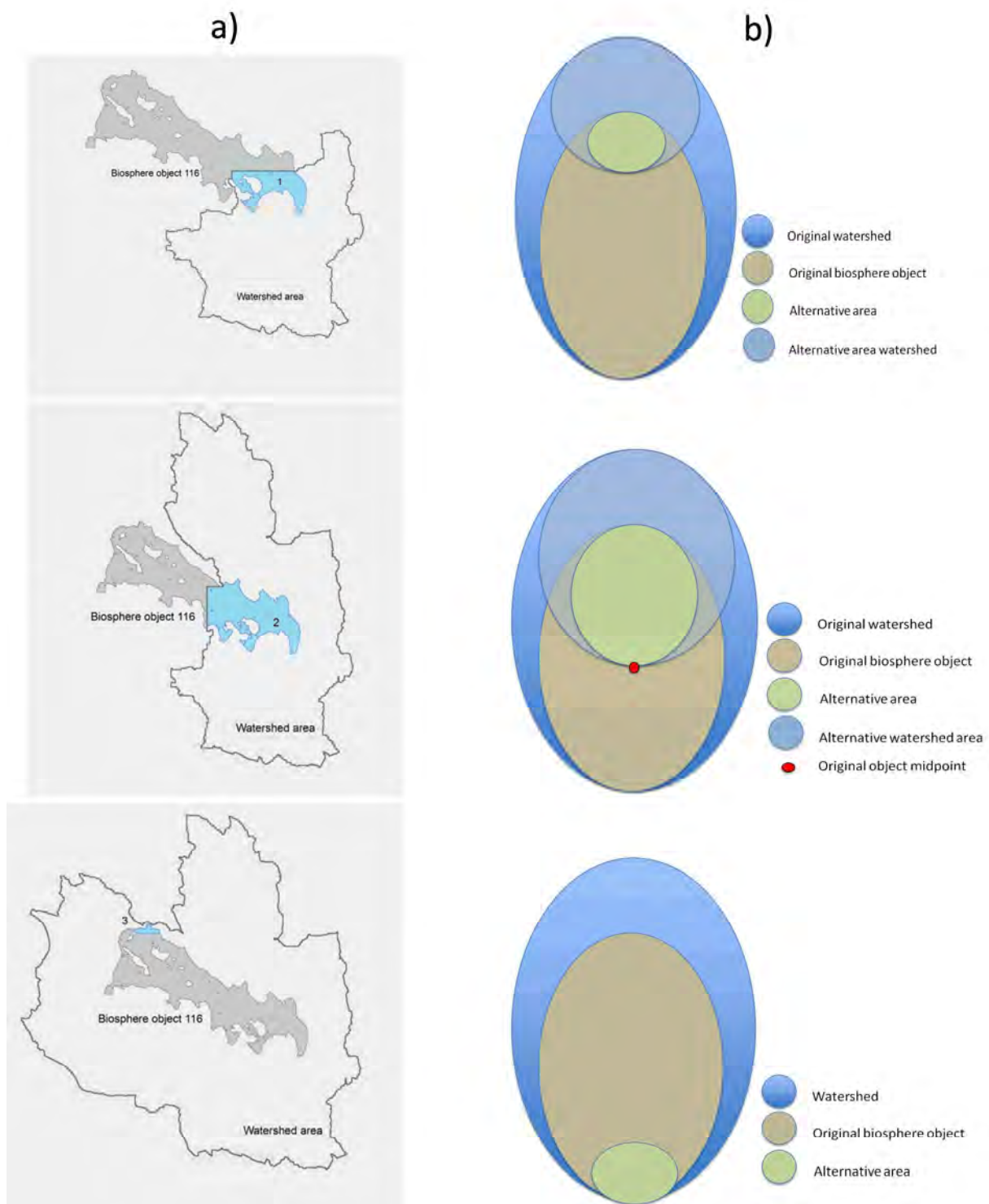


Figure 3-1. Three types of alternative biosphere object subareas used to illustrate effects of object locations and sizes on calculated dose. a) Map projections of the original object 116 (grey), alternative subareas (light blue) and sub-catchment (white): 1 = subarea in the upstream part of the object (top), 2 = subarea defined by midpoint (middle), and 3 = small subarea in the downstream part of the object (bottom). b) Conceptual illustrations of the three subareas. Note that the sub-catchment and the watershed areas are identical for object 116 and subareas within.

3.2 Results

Maximum LDFs for I-129 and Ra-226 from three outlined subareas (Figure 3-1) are tabulated together with the LDF for the original object (excluding exposure from a well drilled into the bedrock) in Table 3-1. In all cases the maximum LDF is achieved in the terrestrial period when the object can be drained and cultivated, and the major exposure route is from ingestion of vegetables (both radionuclides) and other food crops (I-129 only).

I-129 is a weakly sorbing radionuclide ($K_d < 0.7 \text{ m}^3 \text{ kg}_{\text{dw}}^{-1}$ for all regolith layers) with a long half-life ($16 \cdot 10^6 \text{ y}$). This means that for given stationary external conditions and a constant release rate, the time scale of the dynamics of the activity and the steady-state activity concentration are governed by advective transport in all regolith layers.² When steady-state conditions have been reached, total activity concentrations are approximately proportional to the inverse of the advective flux of groundwater through the regolith layers ($q, \text{ m}^3 \text{ y}^{-1}$). In the two regolith layers that contribute to exposure of I-129 when the mire is drained and cultivated, these fluxes correspond to the net vertical flux of groundwater through RegoMid (glacial clay and post glacial clay-gyttja) and the net horizontal flux of groundwater through RegoUp (peat).

In the SR-Site radionuclide model, both these advective fluxes of groundwater were driven by the horizontal surface runoff (Avila et al. 2010), which in turn was proportional to the area of the sub-catchment draining into the lake-mire ecosystem. Thus, it is not surprising that the LDFs for I-129 of the three subareas of object 116 decrease with the size of the sub-catchment, and relate to the LDF of the original object in proportion to the inverse of the ratio of the sub-catchment area (Table 3-1). That is, object 116_3, which has the same sub-catchment as the original object, has a very similar LDF as object 116. The sub-catchments of objects 116_1 and 116_2 are 27 and 55 percent of the original object, respectively. The LDFs are 3.7 and 1.8 times larger than that of the original object, which roughly correspond to 0.27^{-1} and 0.55^{-1} , respectively. Similarly, the LDF-isoclines for I-129 decrease with the area of the sub-catchment, but are insensitive to the size of the subarea (Figure 3-2).

Ra-226 is a moderately sorbing radionuclide ($K_d = 2.5 \text{ m}^3 \text{ kg}_{\text{dw}}^{-1}$ for all regolith layers) with a relatively short half-life (1,600 y, $\lambda = 4.3 \cdot 10^{-4} \text{ y}^{-1}$). As Ra-226 decays, the progeny radionuclide Pb-210 will grow in. Both radionuclides contributed significantly to the dose from ingestion of crop (vegetables in particular), and radionuclide accumulation in the fine grained regolith underlying the peat layer (RegoMid) is the primary source for radionuclides causing exposure when the peatland is drained and cultivated.

² $\text{TC}_{\text{I-129}} \sim \frac{q}{V\theta S} \left(1 + \frac{K_d \rho}{\theta S}\right)^{-1}$, where TC is the proportional rate of transfer of radionuclides out from a regolith compartment (y^{-1}), q ($\text{m}^3 \text{ y}^{-1}$) is the advective flux through the compartment, V is the compartment volume (m^3), θ is the porosity (-), S is the soil saturation (-), K_d is the sorption coefficient ($\text{m}^3 \text{ kg}_{\text{dw}}^{-1}$) and ρ is the regolith bulk density ($\text{kg}_{\text{dw}} \text{ m}^{-3}$). From Appendix A in Saetre et al. (2014).

Table 3-1. Maximum LDFs for I-129 and Ra-226, and geometric data (object and sub-catchment areas) for the “subareas” and the original object 116. “Subarea” LDF refers to the dose conversion factor that would result if all food consumed during a life-time originated from the subarea with the highest concentration of radionuclides. “Whole object” LDF assumes that mixing of crops occurs over the cultivated area claimed by draining the original lake basin (see text for details).

Object	Object size (m ²)	Sub-catchment (m ²)	LDF (Sv y ⁻¹ per Bq y ⁻¹)				Comment
			Subarea		Whole object		
			I-129	Ra-226	I-129	Ra-226	
116_1	2.7 *10 ⁵	3.8 *10 ⁶	1.5 *10 ⁻¹¹	2.5 *10 ⁻¹³	5.3 *10 ⁻¹²	8.8 *10 ⁻¹⁴	small, upstream
116_2	3.8 *10 ⁵	7.8 *10 ⁶	7.4 *10 ⁻¹²	1.4 *10 ⁻¹³	3.7 *10 ⁻¹²	7.0 *10 ⁻¹⁴	midpoint object
116_3	2.7 *10 ⁴	1.4 *10 ⁷	4.1 *10 ⁻¹²	1.3 *10 ⁻¹³	1.5 *10 ⁻¹³	4.5 *10 ⁻¹⁵	very small, downstream
116	7.6 *10 ⁵	1.4 *10 ⁷	4.0 *10 ⁻¹²	7.5 *10 ⁻¹⁴	4.0 *10 ⁻¹²	7.5 *10 ⁻¹⁴	original object

As the advective flux of water through RegoMid (q , m³ y⁻¹) is proportional to the surface area of the sub-catchment in the radionuclide model (see above), the groundwater turnover rate is directly related to the ratio of the sub-catchment and the size of the biosphere object (or actually the saturated pore volume). With a regolith thickness of approximately 2 m (as observed in object 116) and a sub-catchment area that is one order of magnitude greater than the area of the object, the rate of advective transport will be similar to that of radioactive decay in RegoMid. The original biosphere objects analysed in SR-Site all have a relation of the sub-catchment to the object areas of approximately 10:1 (see SKB 2010, Figure 12-4), and consequently this dual regulation of Ra-226 dynamics holds for the diagonal in Figure 3-2.

However, if the sub-catchment area is two orders of magnitude larger than the biosphere object, the turnover rate of the groundwater gets much faster, and then the rate of radioactive decay becomes unimportant for the dynamics and steady-state of the Ra-226 concentration in RegoMid. The behaviour of Ra-226 under these conditions will then be similar to that of I-129. In Figure 3-2, the LDF isoclines above the diagonal reflect such conditions. That is, in this region Ra-226 regolith concentrations decrease with an increased groundwater flux, and consequently the LDF decreases in proportion to the inverse of the size of the sub-catchment (see discussion on I-129 above).

If, on the other hand, the size of the sub-catchment area approaches that of the biosphere object, the turnover rate of the groundwater slows down, and then the rate of radioactive decay becomes the major factor determining the time scale of the concentration dynamics and the steady-state level of Ra-226 in RegoMid. Under these conditions, the steady-state inventory of the radionuclide is reached when the radioactive decay balances the source term for the layer. With a constant input of radionuclides from below, the steady-state inventory becomes independent of the geometry of the system, and the regolith concentration becomes proportional to the inverse of the object area (or, more correctly, to the mass of the regolith layer). In Figure 3-2, the LDFs below the diagonal reflect such conditions. That is, in this region the Ra-226 concentration decreases with an increased mass of the regolith layer, but is insensitive to the advective flux of groundwater. Consequently, the LDF decreases systematically with an increased object area, but changes marginally with the area of the sub-catchment.

The decay chain of Ra-226 produces Pb-210, and for each decay of Ra-226 one Pb-210 atom is formed within a few days. By multiplying the activity of Ra-226 with the decay rate λ of Pb-210, the amount of Pb-210 formed is scaled to activity. Pb-210 is a strongly sorbing radionuclide ($K_d = 43 \text{ m}^3 \text{ kg}_{\text{dw}}^{-1}$ in RegoMid and RegoUp) with a short half-life (22 y, $\lambda = 3.1 \cdot 10^{-2} \text{ y}^{-1}$), and therefore the loss of Pb-210 activity (and the time scale given a constant source term) will be determined only by its decay rate. The source and loss of Pb-210 activity is proportional to the Pb-210 decay rate, and as the primary source of Pb-210 in RegoMid is Ra-226 in the compartment, the Pb-210 activity (and activity concentration) in RegoMid will trail that of Ra-226.

The LDFs calculated for the three explicitly defined subareas of object 116 can be interpreted in the above framework (Table 3-1). Objects 116_1 and 116_2 have a groundwater turnover rate that is similar to that of the original object, and thus both advective transport and radioactive decay are approximately equally important drivers of activity concentrations in RegoMid. The small upstream object 116_1 has object and sub-catchment areas that are approximately one third of the corresponding areas in 116, and as expected the LDFs are approximately three times higher than in the original object. The “midpoint” object 116_2 has a sub-catchment half the size of that of the whole object 116, and an object area that is approximately of the same size as the original object (Table 3-1). The effect of decreased advective transport get “buffered” by an unaffected (and equally important) loss of activity through radioactive decay, and the overall result is that the LDF is 50% higher (rather than twice as large) in the midpoint object as compared to the original object.

Finally, the very small object 116_3 has the original sub-catchment, and thus a relatively high groundwater turnover rate. In this object, radioactive decay has a limited effect on the loss of activity in RegoMid, and consequently the activity concentration is similar to that of the original object and less than most of the effect of radioactive decay. As expected, the LDF of 116_3 is almost twice as large (~70%) as for the original object.

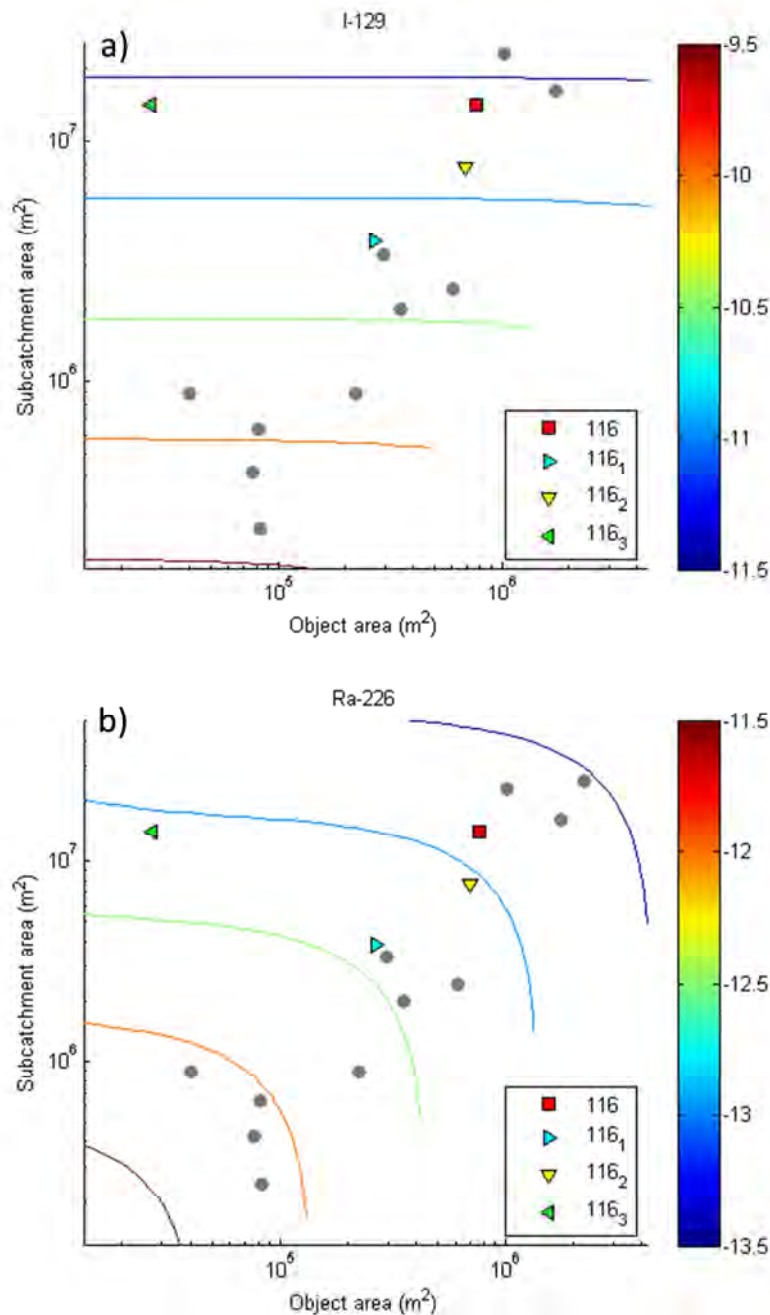


Figure 3-2. Contour plots displaying the effects of object and sub-catchment areas on the maximum LDF for (a) I-129 and (b) Ra-226 in object 116. The size relations of the three calculation cases in Figure 3-1 and the original object are shown as coloured symbols, whereas the size relations of all original SR-Site objects are shown as grey symbols.

In the above example, the effects of the three outlined subareas within biosphere object 116 on the LDF were limited to a factor of 3.8 and 3.3 for I-129 and Ra-226, respectively (Table 3-1). The contour plots in Figure 3-2 show the LDF-response to the sizes of objects and sub-catchment areas to be of a much broader range. However, any real set of lake and sea basins has physical limits to the size of the local catchment for a specified discharge area of groundwater from the repository. In the case of

lake basin 116, the smallest size of the sub-catchment is approximately that of subarea 116_1 (Figure 3-1). The smallest size of the discharge area is, on the other hand, limited by the size of the discharge plume. A re-evaluation of the spread of discharge points (Joyce et al. 2010) suggests that 75% of particles from a canisters in a high groundwater flow position³ would typically be captured in an circular area of 20 000 to 65 000 m² (median and mean of 35 canister positions). This size range coincides with the object area of the smallest subarea 116_3 (27 000 m²).

In the SR-Site assessment, the discharge areas where radionuclides accumulate are located in mires (or lake-mire complexes) when the object is above sea level. These areas can only be cultivated after they have been drained. Such an enterprise requires much work and would for practical reasons most likely involve conversion of the full lake/wetland system for cultivation. Moreover, if the mire in object 116 (or any other biosphere object) is drained it is not reasonable to assume that a person (or an exposed group) would obtain food from the area with the highest concentrations during the entire adult lifetime (50 years). Horizontal mixing due to ploughing, rotation of land, and mixing through storage and processing of crops (e.g. milling), all make it reasonable to average radionuclide concentrations in the diet over the full land area claimed by the draining enterprise. In this case, that would be averaging annual dose across the area of the original lake (i.e. object 116).

Thus imposing reasonable constraints on the size of the catchment and the subarea, the concentration in food produced on the subarea will not exceed a factor 3.7 of that in the original object for I-129, and a factor of 5 for Ra-226 (data behind Figure 3-2). Moreover, if mixing due to e.g. land rotation and storage is accounted for, the highest LDF of both I-129 and Ra-226 would occur on a large contaminated area with a small local catchment, but would not exceed a factor of two of the originally calculated LDF. It can also be noted that the LDFs for both I-129 and Ra-226 from a small area in the downstream part of an object will be more than one order of magnitude smaller than that of the original object, if dilution due to cultivation and crop storage was accounted for (i.e. 4 and 6% of the original LDF, cf. the "Whole object" LDFs in Table 3-1).

³ The travel time of water from the canister position in the repository to the surface is less than or equal to 30 years.

4 Recent studies in SR-PSU

This section describes a modelling activity performed within the SR-PSU safety assessment of an extended SFR repository in Forsmark. This safety assessment was submitted to SSM in December 2014, as a part the application to extend and operate SFR. The study summarised below differs from the one in the preceding section in that alternative object delineations are defined based on different types of arguments, e.g. hydrological modelling and land use. Moreover, the radionuclide model for the biosphere and associated parameter values were updated in the SR-PSU assessment (Saetre et al. 2013), and the radionuclides examined did not include Ra-226 and I-129. Nevertheless, the sensitivity calculations summarised in this section are relevant for discussing the effects of object delineation on model output in a broader sense.

4.1 Alternative object delineations

The methodology for delineation of biosphere objects is based on knowledge of the ecosystems in Forsmark and processes affecting the fluxes and distribution of elements in these. In the SR-PSU safety assessment, alternative methods for delineating biosphere objects were applied in order to examine how the object delineation may affect object properties and the environmental concentrations that result from a constant release of radionuclides. The analysis summarised below was presented in the SR-PSU Biosphere synthesis report (SKB 2014), to which the reader is referred for further details (including additional results). Four alternative delineations were derived from different assessment perspectives and were applied to biosphere object 157_2 (Figure 4-1), which is the biosphere object receiving almost all potentially contaminated groundwater in SR-PSU:

1. *Areas with upward hydraulic gradients (UpwGrad)*. The original biosphere object 157_2 was outlined based on particle discharge at the bedrock-regolith interface. For this alternative delineation, it is assumed that all radionuclides are released to areas that are defined as discharge areas all the way from the bedrock to the surface. Discharge areas are defined based on flow modelling results from a MIKE SHE surface hydrology model, and calculated using head differences between adjacent calculation layers. Head differences were calculated for layers in the regolith, in the bedrock located just below the regolith, and in the bedrock at a depth of approximately 60 m. Areas defined as discharge areas at all three levels were selected as an alternative delineation of biosphere object 157_2 (Figure 4-1a).
2. *Wetland areas (Wetl)*. In this delineation it was assumed that all radionuclides are released to the area of the object that has wetland properties. Moreover, it was assumed that wetland areas within the object are connected through the flow of surface water and groundwater, at least for parts of the year when they are flooded. In Sweden, wetlands are defined as areas which for most of the year are below or just above the local groundwater level (Löfroth 1991), and where hydrophilic (i.e. moisture-loving) species make up at least 50% of the vegetation. Considering the calculated yearly groundwater fluctuations in the object, this alternative selected and outlined the areas where the yearly average of the groundwater level was above or not more than 25 cm below ground level as wetland areas. The TWI-projected (Topographical Wetness Index) vegetation of the outlined wetland areas confirmed that this criterion was reasonable. That is, the outlined areas were dominated by wetland vegetation (open wetland or wetland forest), and were connected by wetland vegetation (Figure 4-1b).
3. *Main area for discharge points (HD-disch)*. In the delineation based on discharge points from DarcyTools, it was assumed that all radionuclides are released only to the area with the highest density of discharge points. The groundwater flow modelling tool DarcyTools was used to identify particle discharge locations at the interface between rock and regolith for temperate climate conditions (Odén et al. 2014). Discharge locations for particles released in stationary, DarcyTools-

calculated groundwater flow fields at different time steps and with different bedrock setups were identified. In the particle tracking, 1,000,000 particles were released uniformly, and proportional to facility volume, in SFR 1 and SFR 3, respectively. Based on results with the base-case setup of the rock, which was the setup also delivered to MIKE SHE, the area with a high density of discharge points was selected as an alternative delineation of biosphere object 157_2 (Figure 4-1c).

4. *Potential arable land (Arabl)*. In the SR-PSU landscape development model, a future landscape is described in which most of the potential arable land is used (SKB 2014, Chapter 5). This case is built upon a historical perspective, where the agricultural use of the landscape was at its maximum (around 1940), and the potential of using the arable land for at least 50 years of continuous farming. Accordingly, wetlands need to have sufficiently thick soil layers for cultivation to make draining feasible. Thus, for this delineation it was assumed that the combined thickness of peat, postglacial clay and glacial clay was at least 0.5 m after drainage, accounting for the compaction and oxidation of peat and postglacial clay associated with drainage. When these criteria are applied on biosphere object 157_2, only a small area is regarded suitable for long-term agricultural practices (Figure 4-1d)

Each of the alternative delineations reflects a stylised approach of outlining a biosphere object derived from a different assessment perspective. Thus, the resulting objects should not be seen as equally likely representations of areas affected by deep groundwater from the repository. For example, discharge areas with a steady upward flux of groundwater from the bedrock to the surface (1), and open wetland areas connected by a horizontal exchange of surface water (2), are likely to receive most of the radionuclides discharged to the object. On the other hand, the area superimposed on bedrock with a high density of discharge points (3) and the area representing potential arable land (4) illustrate aspects of potential variations in object-specific properties, but they were derived from hypothetical “what if” perspectives.

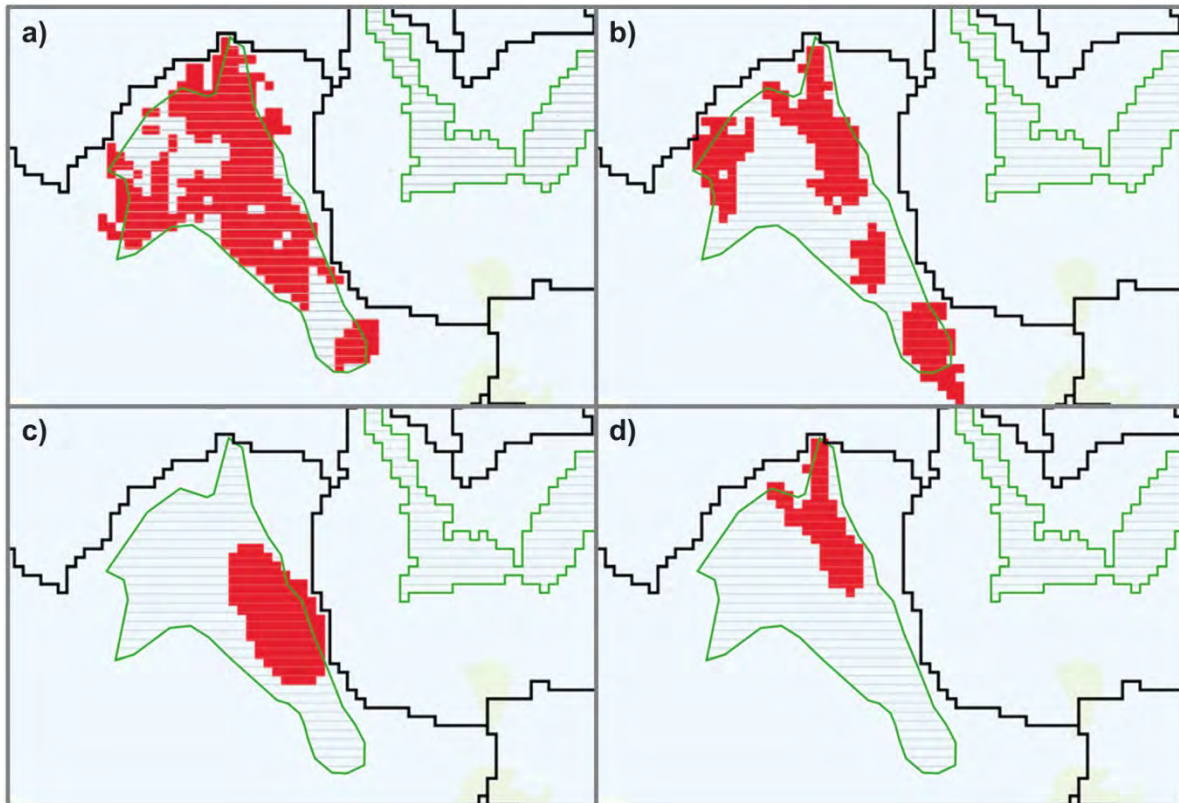


Figure 4-1. Alternative delineations of biosphere object 157_2 in the SR-PSU safety assessment. The green line indicates the original object and the red areas the alternative outlines of the biosphere object. a) Areas with upward hydraulic gradients (from bedrock to surface). b) Wetland areas (water above surface or not deeper than 0.25 m below the surface). c) Area with a high density of repository discharge points at the bedrock-regolith interface. d) Potential area for cultivation, after drainage of mire.

The alternative delineations resulted in a range of object sizes spanning from 168,000 m² (original object) to 29,000 m² (potential area for agriculture) (Figure 4-2). As expected there were systematic differences in the average depth of regolith layers between alternative delineations. In relative terms, the largest variation was found in the thickness of glacial clay (the RegoGL layer in the radionuclide model for the biosphere, see Saetre et al. (2013)) and peat (the RegoPeat layer) that varied by factors of 10 and 3, respectively. For example, the thickest peat and glacial clay layers were found in the area which could potentially be drained and cultivated, whereas the thinnest layers of glacial clay were found in the area with a high density of discharge points (Figure 4-2a).

Water balances and groundwater flux rates between regolith layers were determined for each of the delineated areas (see Werner et al. (2013) for details). As radionuclides are expected to enter the biosphere object from the geosphere, upward water fluxes are key parameters for the transport of radionuclides through the soil horizon. Area-specific upward fluxes (m³ m⁻² y⁻¹) varied by a factor of two to three between the outlined areas (Figure 4-2b). As expected, the discharge area had the highest flux rates in the lowest regolith layers, whereas the upward flux of groundwater between peat layers was highest in the wetland area. Between objects, differences in total upward fluxes of groundwater (m³ h⁻¹) were much larger, and varied by a factor of 10 to 20.

As expected from the area-specific fluxes, variation in total flux was primarily driven by the size of the outlined objects (Figure 4-2c). The horizontal flux of water from surface peat out of the area was

similar in all outlined objects, with the exception of the area with a high density of discharge points, where the flux was approximately half of that in the other areas. This was expected as this delineation was elevated above the others and had a somewhat smaller catchment area.

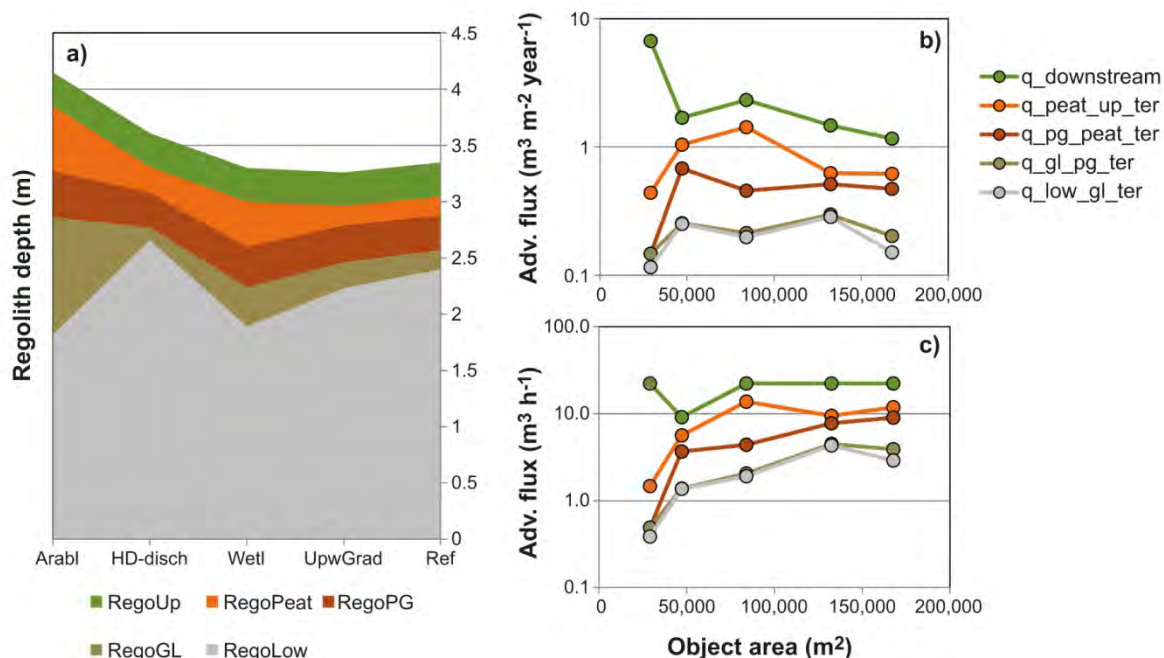


Figure 4-2. Regolith and hydrological flux properties of biosphere object 157_2 in SR-PSU, and alternative delineations (see text). a) Regolith depth, alternative delineations ordered from smallest (Arabl) to largest (UpwGrad) areas. b) Area-specific flux of groundwater as a function of object surface area. Grey, light brown, brown and orange indicate upward fluxes from till (RegoLow), glacial clay (RegoGL), post-glacial clay (RegoPG) and deep peat (RegoPeat), respectively. Green represents horizontal flux of surface water from surface peat out of the object. c) Total groundwater fluxes summed over the area of the object.

4.2 Transport and accumulation of radionuclides for the alternative delineations

In the simulations, 1 Bq y⁻¹ of C-14, Cl-36, Mo-93 and Ni-59 was released to the till (the RegoLow layer) in each of the alternatively outlined areas, and the resulting environmental concentrations were compared with those obtained for the original object. The simulations were run until 20,000 AD, assuming landscape development and ecosystem parameters from the base case of the SR-PSU biosphere modelling. In addition, object-specific parameters were derived from each of the outlined areas, including object area (time-dependent), all hydrological flux rates, and regolith depths. Detailed results on environmental concentrations are presented in SKB (2014). In summary, these were as follows.

Environmental concentrations of radionuclides in areas receiving a constant input of radionuclides were affected by object size, regolith thickness and hydrological fluxes associated with each of the alternatively outlined areas. Of these factors, groundwater fluxes diluting the released radionuclides were perhaps the most important for explaining variations between the outlined areas.

The vertical groundwater flux in the SR-PSU radionuclide model is the product of the object area and the area-specific flux, which in turn is influenced by both topography and the regolith profile. In this analysis the surface area of the outlined objects varied by a factor of five, whereas the area-specific flux varied by a factor of 2.5 (see above). Thus, object size was the most important factor explaining dilution of radionuclides in below surface regolith layers from a unit release rate (see, for example, differences in Figure 4-3a). However, it should be noted that variations in groundwater fluxes will also affect the discharge of radionuclides from the repository. This effect is not accounted for in the present analysis.

The horizontal flux of surface water is primarily determined by the size of the local catchment area (the sub-catchment). Three of the outlined areas had a local catchment similar to that of the original object. The area outlined based on a high density of bedrock discharge points was located higher in the terrain, and thus had a smaller local catchment area (approximately half of the original one). Since the variation in the size of the local catchment was small, the outline of the biosphere object had a limited effect on the concentration of low-sorbing and non-volatile radionuclides in surface peat (see Cl-36 and Mo-93 in Figure 4-3a, c). On the other hand, as degassing dominated horizontal groundwater transport of C-14, the size of the outlined area had a direct and significant effect on concentrations of C-14 in surface peat for this radionuclide (Figure 4-3b).

If the potential for radionuclide accumulation is large in deeper regolith layers, then only small amounts of radionuclides will reach surface layers during the simulation period. Thus, concentrations in regolith of medium and highly sorbing radionuclides depended as much on accumulation dynamics as on steady-state conditions. A continuous accumulation in the thick glacial clay layer in the smallest outlined area reduced Ni-59 concentrations in surface peat and agricultural soil, as compared to the concentrations of more mobile radionuclides (Figure 4-3b-d).

Although alternative outlines of the primary biosphere objects had a clear effect on environmental concentrations, the effect was limited. That is, the concentrations in the three largest alternatively outlined areas were typically not more than two or three times larger than the concentration in the original object. The variation in environmental concentrations could in most cases be linearly related to a first-order effect of a change in hydrological fluxes or in regolith depths. Even for environmental media that were influenced by several parameters, the effect on concentrations did not exceed a factor of 1.5 larger than that due to the change in the most influential parameter.

On the other hand, in the smallest outlined object, concentrations in till pore water were elevated by a factor of eight (all radionuclides), concentrations in drained and cultivated soil were elevated by a factor of ten (C-14, Cl-36 and Mo-93) and the concentration in surface peat was elevated (C-14), or decreased (Ni-59), by a factor of five. However, the increased concentrations in the smallest object is conditioned on the “what if” assumption that all radionuclides would be released to this area, which is not likely to occur.

It is reasonable to expect that the variation in exposure of future human inhabitants and of non-human biota would be proportional to the change in environmental concentrations. For human inhabitants, ingestion is the primary route for exposure to long-lived radionuclides. As the production of the biosphere object limits exposure of inhabitants foraging the landscape, the effect of an increased concentration in food would be offset by a decreased availability of food in a smaller object.

For non-human biota with a limited home range and for humans cultivating the mire, there would be no dilution from areas outside the biosphere object, unless the support area exceeded the biosphere object. However, note that the object representing possible arable land (derived from hypothetical “what if” perspectives) would only suffice to support one family with arable land after draining, and would provide less than a third of the hay needed for the most exposed group given infield-outland agriculture (SKB 2014). Thus, for biosphere objects of this size (~3 ha) it would be reasonable to apply the risk criteria for a small exposed group (10^{-5} year⁻¹ rather than 10^{-6} year⁻¹) (SSMFS 2008:37).

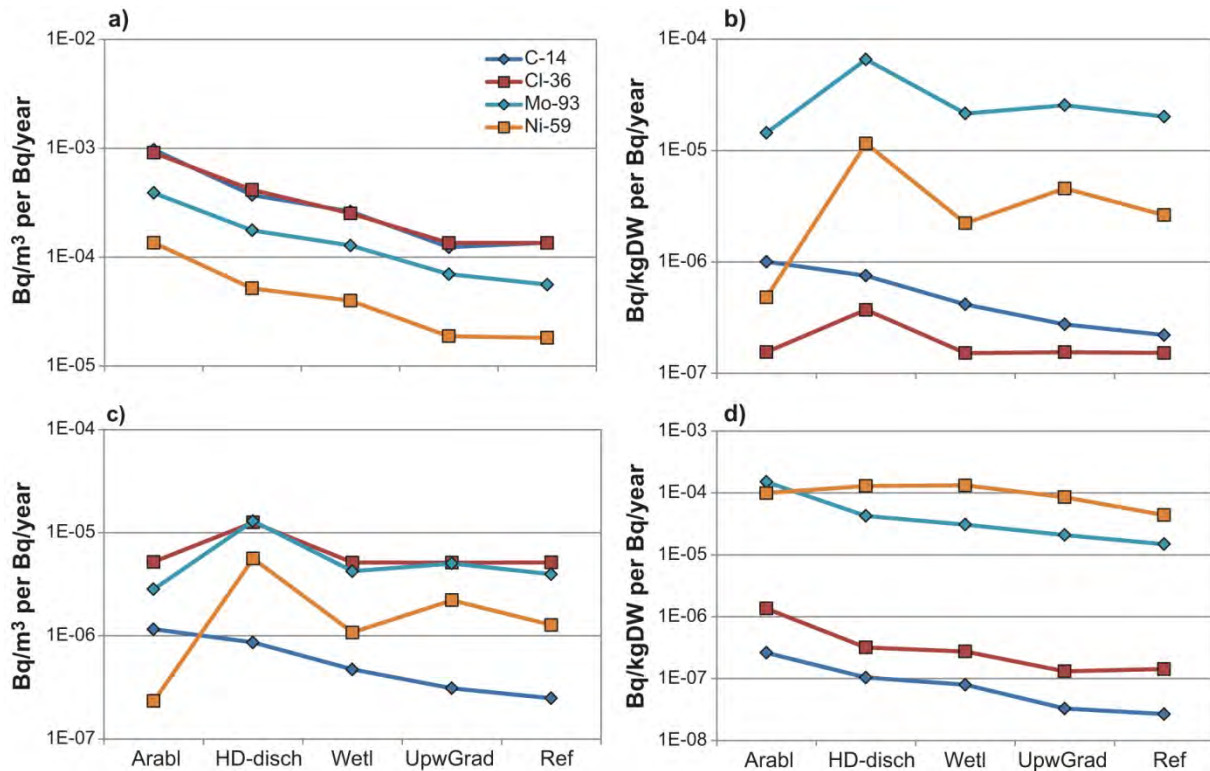


Figure 4-3. Concentrations of four radionuclides in environmental media, which may cause exposure of humans and non-human biota, as a function of object delineation. a) Pore water concentrations in till (RegoLow) available through a dug well. b) Total concentrations in surface peat (RegoUp). c) Concentrations in surface water in contact with peat. d) Concentrations in drained and cultivated soil. Values are maximum values for simulations until 20,000 AD under temperate climate conditions. The alternative object delineations are listed in size order within each figure (smallest to the left) with the original object to the right, see text for further description of the different delineations.

5 Discussion and conclusions

During the safety assessment SR-Site a landscape methodology was used to identify potential discharge areas for groundwater from the repository. The method focused on identifying sea basins, where the central areas develop into lake basins that ultimately are filled with lake sediments and peat. The method resulted in reasonable and *a priori* definable objects in the landscape representing potential areas for discharge of deep groundwater, where the two parts of the objects (the terrestrial and the aquatic parts) represent separate ecosystems. The criteria used in the delineation of the objects provided a reproducible method that allowed identification of future objects with boundaries that could be characterised with a relatively high confidence based on the digital elevation and shoreline displacement models.

The method resulted in a spectrum of objects with respect to the size of the lake basin (mire) and the local catchment area. Additionally, one SR-Site object (121) was further sub-divided, to examine the consequences of introducing two additional types of biosphere objects: a small upstream wetland that does not go through a lake stage (121_3) and a stream object (121_2) characterised by running water. In the safety assessment, the biosphere object resulting in the highest LDF was selected for each radionuclide, and this set of dose conversion factors was used for the dose and risk calculations. The dose from a drilled well was added to the dose resulting from living in and utilising natural resources (including cultivated crops) from the biosphere. For the dose calculations it was further assumed that the entire object is used for food production. This means that even if the object is heterogeneously contaminated the mixing that occurs through food production will result in a life-time dose that is similar to that obtained by averaging over the entire object.

The results from the geohydrogeological simulations confirmed that the majority of discharge points fall within an identified object. However, the discharge points are only an ideal representation of inert particles, without any dispersion in time and space and are regarded as confirming the approximate location of the discharge area, but not as very representative for the size of the contamination “plume footprint”.

An uncertainty analysis in SR-Site considering object and catchment area sizes and the discretisation of the lower regolith showed that the maximum LDF values were robust, because the variations in these parameters did not significantly affect the LDF ($< \text{factor } 2$) or that the worst case was already taken into account. The analysis showed that concentrations could change dramatically in a compartment, but also that other factors (e.g. drinking water) were more important for the dose. Thus, from the assessment perspective, i.e. what affects the final results, the confidence is high that the methodology gives a reasonable dose estimate, even if there are areas that have higher or lower concentrations than those used for the dose calculations.

The calculations in Section 3 demonstrate that the location of the discharge area within a biosphere object may affect the soil concentrations of radionuclides and the LDFs resulting from ingestion of cultivated crops. In these simulations, LDFs were elevated as compared to the original simulations (with a homogenous discharge) due to reduced groundwater flux rates, and the effect on the LDF varied with radionuclide. The LDF was elevated by no more than a factor four for I-129, whereas the LDF for Ra-226 was a factor five higher for a small discharge area. However, if reasonable mixing due to the cultivation of land and processing of crops was accounted for, the effects of a heterogeneous soil concentration within the lake basins was limited to less than a factor of two.

In SR-PSU, alternative delineations of biosphere object 157_2 also showed that the size of the primary discharge area affected environmental concentrations within till, surface peat and the soil resulting from draining and cultivating a peatland. Variations in hydrological flux rates were the main drivers of variations in environmental concentrations (of non-volatile radionuclides), and regolith depth had some additional effects on the results. Moreover, the effects of object size on activity concentrations varied with environmental media and properties of radionuclides. Dilution from cultivation practices

and processing of crops from the drained peatland was not accounted for in the analysis, but it was pointed out that the smallest outlined area (30,000 m²) could only support a family of self-sustained farmers, and consequently the risk criteria for a small exposed group would be reasonable to apply in such cases.

In summary, the discharge of radionuclides with groundwater to a biosphere object (the size of a lake basin or a mire) is unlikely to be homogenous, and groundwater flux rates and regolith depths will vary within the biosphere object. Areas with a high upward flux of groundwater are likely to receive more radionuclides than other areas, whereas the dilution of radionuclides reaching areas with low groundwater flux rates will be reduced. Thus, environmental concentrations can be expected to vary spatially within any outlined biosphere object. In this report we have examined the effects of alternative assumptions on the area receiving radionuclides. Accounting for reasonable dilution from cultivation practices and processing of crops from the drained peatland, the LDFs from hypothetical subareas can either be reduced or elevated, but the effects of the most pessimistic assumptions on the size and position of the subarea within a biosphere object is limited to less than a factor of two. As this analysis has not considered the exposure from a well in the bedrock (an independent and equally important exposure pathway for Ra-226 in SR-Site), the impact on the LDF of Ra-226 in an assessment perspective is expected to be even less.

We conclude that release to the entire object is a reasonable representation of the LDF that would result from averaging across areas of higher and lower radionuclide concentrations. That is, the spatial dilution that may occur by assuming a homogenous release of radionuclides to the biosphere object is, on the scale of a drained lake-mire complex, counter-balanced by mixing through land use and food storage and processing. Thus, we are confident that the methodology used, which considers a wide range of object and catchment sizes and then effectively considers the worst case in the safety assessment, gives reasonable LDFs even if the release is restricted to a subarea associated with the release plume from a single canister.

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