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The impact of low and intermediate-level radioactive waste on humans and the environment over the next one hundred thousand years

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ABSTRACT

In order to assess the potential radiological risk to humans and the environment from a geological repository for radioactive waste, a safety assessment must be performed. This implies that the release and transfer of radionuclides from the repository into the surface environment are calculated and that the effects in the biosphere are evaluated for an assessment period up to one hundred thousand years according to Swedish regulations. This paper discusses the challenges associated with the modelling of surface ecosystems over such long time scales, using the recently completed assessment for the extension of the existing repository for the low- and intermediate-level nuclear waste (called SFR) in Forsmark, Sweden as an applied example.

In the assessment, natural variation and uncertainties in climate during the assessment period were captured by using a set of climate cases, primarily reflecting different expectations on the effects of global warming. Development of the landscape at the site, due to post-glacial isostatic rebound, was modelled, and areas where modelling indicated that radionuclides could discharge into the biosphere were identified. Transfers of surface water and groundwater were described with spatially distributed hydrological models. The projected release of radionuclides from the bedrock was then fed into a biosphere radionuclide transport model, simulating the transport and fate of radionuclides within and between ecosystems in the landscape. Annual doses for human inhabitants were calculated by combining activity concentrations in environmental media (soil, water, air and plants) with assumptions on habits and land-use of future human inhabitants. Similarly, dose rates to representative organisms of non-human biota were calculated from activity concentrations in relevant habitats, following the ERICA methodology.

In the main scenario, the calculated risk for humans did not exceed the risk criteria or the screening dose rate for non-human biota, indicating that the repository design is sufficient to protect future populations and the environment. Although the combination of radionuclides, land-uses/habitats, type of most exposed population and area of exposure that contribute most to the total dose shifts over time, the total calculated dose shows limited variability. Significant reductions in the dose only occur during submerged periods and under periglacial climate conditions. As several different water and food pathways were equally important for endpoint results, it is concluded that it would be difficult to represent the biosphere with one or a set of simplified models. Instead, we found that it is important to maintain a diversity of food and water pathways, as key pathways for radionuclide accumulation and exposure partly worked in parallel.

1. Introduction[2]

When addressing the potential effects from a geological repository for low- and intermediate-level nuclear waste in Sweden, time frames of up to 100,000 years are of interest. For a geological repository for spent nuclear fuel even longer time frames, up to one

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[2] More details of the biosphere assessment can be found in the project reports SKB (2014a, e) and references therein available from www.skb.se/publications, from where also all other SKB report listed below can be downloaded.

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million years, have to be considered according to the Swedish regulations (SSM, 2008). In Sweden the Forsmark site has an existing low- and intermediate-level waste repository (LILW), 'Slutförvaret för kortlivat radioaktivt avfall' (a.k.a. SFR), and the location has been selected for a permanent geological repository for spent nuclear fuel (high-level waste; HLW). Depending on if it is a HLW or LILW repository, the focus and time-frames in safety assessments can be different. This and other differences between assessing a HLW repository (SR-Site, cf. Kautsky et al., 2013a) and a LILW (SKB, 2014a) are discussed in this article.

SFR has been operated by the Swedish Nuclear Fuel and Waste Management Co (SKB) since 1988. A number of safety assessments have been performed for the repository since SKB received permission to start building SFR in 1983. The purpose of a safety assessment is to evaluate if human health and the environment are protected from harmful effects of ionising radiation caused by the repository. In December 2014 a new license application was submitted to the authorities containing a safety assessment for an extended repository (SKB, 2014a). The key findings regarding the biosphere part of this safety assessment (SKB, 2014b) are highlighted in this paper.

Regulations from the Swedish authorities require a safety assessment covering one hundred thousand years following repository closure (SSM, 2008). In that time frame, the state of the repository system and its surrounding environment can be expected to change. Due to the very long time-scales considered, uncertainties concerning the properties of future surface ecosystems, and the characteristics and habits of future human inhabitants and non-human biota can only be taken into account by using simplifying assumptions. Intentionally, the assessment is reasonably cautious for a sufficiently robust demonstration of compliance aiming at over-rather than underestimating radiological consequences without being unrealistic.

The biosphere part of the safety assessment of the extended SFR builds on those made previously, for SFR and for the planned repository for spent nuclear fuel in Sweden. Between 2002 and 2008, SKB performed site investigations for a repository for high-level waste (HLW) in Forsmark (SKB, 2008). Thereby, the past and present biosphere conditions at Forsmark have been described thoroughly in a number of papers and reports. Several adaptations and improvements were necessary to better handle certain radionuclides (e.g. C-14) and scenarios specific to the 2014 safety assessment of SFR, which is called SR-PSU. Additional site investigations were performed 2010–2012 for the SFR extension project (SKB, 2013).

The present paper summarises some of the challenges met within the biosphere part of the SR-PSU safety assessment (Fig. 1), the methods and models developed to calculate transport and dose in surface ecosystems, and presents selected results from the main scenario. The intention is to give an overview and some highlights of the biosphere program in the most recent safety assessment performed in Sweden, thereby providing both a brief state of the art on radionuclide transport and dose modelling in surface ecosystems within the Swedish program and an illustration of some aspects specific to this assessment of low- and intermediate-level waste (LILW).

2. Input data and models

The Forsmark site represents a typical coastal area at the shoreline of the Baltic Sea in northern Uppland, Sweden, with a small-scale topographic variation The majority of the landscape is covered by a thin regolith layer mainly consisting of till. The rapid shoreline displacement has strongly affected landscape development, and still causes a continuous and relatively predictable change in the abiotic and biotic environment. The first parts of Forsmark emerged from the sea around 500 BC resulting in a young terrestrial system that contains a number of new-born shallow lakes and wetlands. At the site the LILW repository is operating as well as the three Forsmark nuclear power reactors. Details concerning the Forsmark site can be found in Lindborg (2008) and SKB (2008).

2.1. The SFR repository

SFR consists of a set of disposal chambers situated in rock at c. 60 m depth beneath the present-day sea floor (Fig. 2). It is built as a passive repository for the storage of short-lived low- and intermediate-level radioactive waste. The radioactive waste is operational waste from the Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, and radioactive waste from other industries, research institutions and medical care. An extension with rock vaults at c. 120 m depth is planned, in order to enable storage of decommissioning waste from the Swedish nuclear power plants (Fig. 2; see SKB, 2014a for details).

The radioactive inventory of the waste to be disposed of in SFR is dominated by short-lived radionuclides. This means that a large portion of the radioactivity deposited in SFR will decay substantially during the operational phase, i.e. up to about 2075AD. After 1000 years only 2% remains of the total activity content. Initially, Ni-63 dominates the activity, but after about 600 years Ni-59 and C-14 will become dominant (SKB, 2014a).

2.2. Climate change

During the long time period covered by the safety assessment (100,000 years), the climate is expected to vary, and both warmer and colder periods than the present are anticipated. Current scientific understanding of the climate system suggests that the climate evolution during the coming 100,000 years will differ from the past climate variability. It is very likely that the anthropogenic release of CO_2 into the atmosphere, together with the future natural variation in insolation, will result in the present Holocene interglacial being considerably longer than previous interglacials (e.g. Berger and Loutre, 2002; Näslund et al., 2013; SKB, 2014c).

In order to include uncertainties in climate evolution for the coming 100,000 years, a number of climate cases are considered as a basis for the safety assessment (Näslund et al., 2013). Three climate cases are defined to span the range in future climate evolution associated with low, medium and high human carbon emissions (i.e. different degrees of global warming): *the early periglacial climate case* with a periglacial period at 17,000 AD; *the global warming climate case* with the earliest periglacial period at 52,000 AD; and *the extended global warming climate case* without periglacial periods in the assessment period. Among them, *the global warming climate case*, which describes a climate evolution with a medium degree of global warming, is used in this article. The climate cases used in the assessment of the SFR repository are described in detail in SKB (2014c).

Information from the various climate cases is used to define parameters in the landscape development models, radionuclide transport models, and for determining presence and land-use of human inhabitants and non-human biota at the site for the calculation of radioactive dose. Since the coming one hundred thousand years are expected to be affected by global warming, processes such as leaching of soils and periglacial environments in general are comparatively more important in the SR-PSU LILW assessment than in the one million year time frame of the HLW assessment (Näslund et al., 2013), where processes related to glaciation (erosion, isostatic changes) are additional factors of high importance.

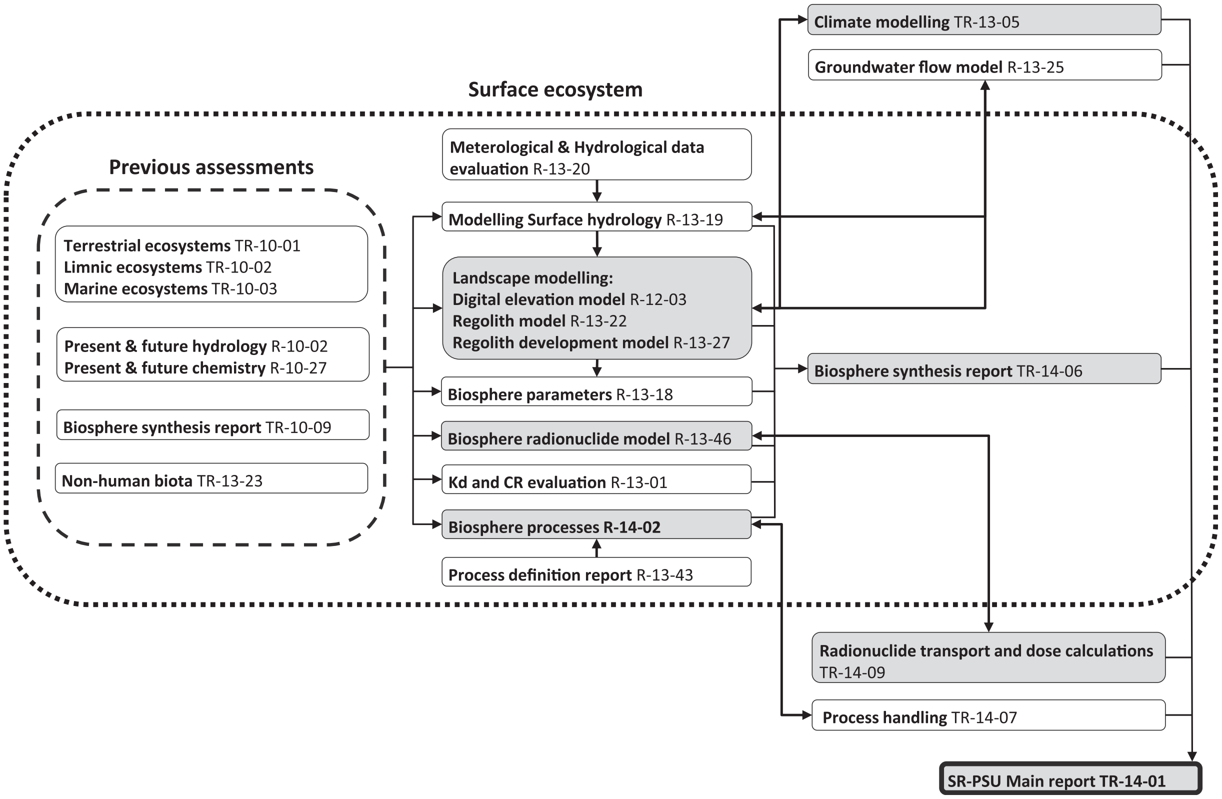

Fig. 1. Relationships between the major activities in the biosphere part of the safety assessment of the low- and intermediate-level repository SFR. Interactions with other parts of the safety assessment (e.g. climate and geohydrology) are also shown. The parts of the safety assessment discussed in this article are marked grey. Codes (R-xx-xx, and TR-xx-xx) refer to SKB report numbers where the activities are thoroughly described. The reports can be downloaded from the SKB homepage www.skb.se/publications and are associated to the SR-Site and SR-PSU safety assessments.

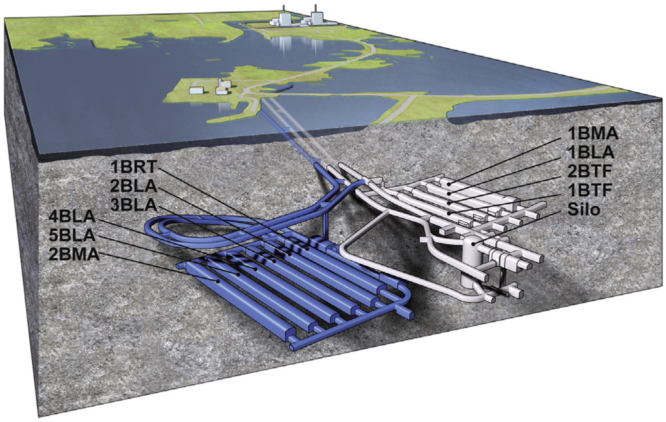

Fig. 2. Illustration of the SFR repository for short-lived low- and intermediate-level radioactive waste. White disposal chambers represent the existing repository, and blue the planned extension of SFR. The tunnels to the repository extend to the surface buildings (centre of picture). The planned extension (blue) will function in the same way as the existing repository, but the rock vaults will be longer and situated at a greater depth (details in SKB, 2014a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Landscape development

Due to isostatic rebound since the last glaciation, there is a shoreline displacement in the Forsmark area, and a continuous landscape development initiated and also otherwise affected by this process. Radionuclide transport and exposure of humans and non-human biota are dependent on climate and landscape development (Kautsky et al., 2013a; Lindborg et al., 2013). Radionuclide transport is dependent on regolith depths and ecosystem types, and humans and biota can utilise the Forsmark area differently dependingon landscape characteristics, e.g. the area can be utilised for agriculture when situated above sea level, and for fishing when submerged.

The current understanding of the spatial and temporal variations in present and past site conditions can be used as an analogy for future conditions (Kautsky et al., 2013b). At the end of the latest deglaciation the Forsmark area was covered by approximately 150 m of water and the nearest shoreline was situated some 100 km west of Forsmark (Söderbäck, 2008). Thereafter, the isostatic rebound has decreased from c. 3.5 m/100 years to a present rate of c. 0.6 m/100 years, and is predicted to become insignificant around 30,000 AD.

As the present sea floor is uplifted, marine sediments are exposed to wave erosion, and sea basins are isolated and become lakes and wetlands. The stratigraphy and thickness of regolith layers will consequently change with time. Fine grained sediments will be redistributed in the coastal area. New lakes will become progressively shallower as sediments accumulate, and the expansion of mire vegetation will create peat-covered areas as shallow lakes gradually change into mires (Lindborg et al., 2013; SKB, 2014b).

In the safety assessment for SFR, a digital elevation model (Strömgren and Brydsten, 2013), a model describing the present depth and stratigraphy of regolith (Sohlenius et al., 2013), and a coupled regolith and lake development model (Strömgren and Brydsten, 2013) are used to describe the landscape development.

Together, these models are used to describe three-dimensional projections of surface geology for successive steps in time in a landscape development model. From these projections maps showing water depth, present shoreline and lake positions, and thickness of the surface regolith layers or vegetation type over time were generated and parameters describing specific areas extracted (SKB, 2014b). In addition to affect vegetation types and geometries like regolith and water depths, the landscape development and climate changes affect hydrology, water flows in marine basins (Werner et al., 2013), and the structure and function of surface ecosystem (SKB, 2014b).

The development of the landscape at the site due to land uplift, under the global warming climate scenario and certain assumptions regarding human land use, is illustrated in Fig. 3. The four time-points show the withdrawal of the sea over time and the infilling of sea bays, which become wetland/mire areas (with or without an intermediate lake stage) and then fully terrestrial land (arable land, mixed coniferous forest, or pine forest on bedrock). At 5000 AD the sea has completely withdrawn from the vicinity of SFR. Of the land area available then, only a relatively small fraction is possible to cultivate; the major parts are tills, rock outcrops or other soils that are difficult to manage but possibly to use for grazing, hunting and forestry. At 20,000 AD the entire model area is situated on land and large areas are available for agriculture. A detailed analysis of the landscape development can be found in (SKB, 2014b).

2.4. *Groundwater transport and discharges*

In order to understand where potential discharge of radionuclide-bearing groundwater originating from SFR could reach the surface ecosystems and to quantify transport parameters such as travel times, Odén et al. (2013) modelled groundwater flow and non-reactive particle transport from the repository during the period after it has been closed. The location and density of the emerged particles were mapped at the bedrock surface (Fig. 4), and based on these results potential discharge areas were outlined (Berglund et al., 2013; SKB, 2014b).

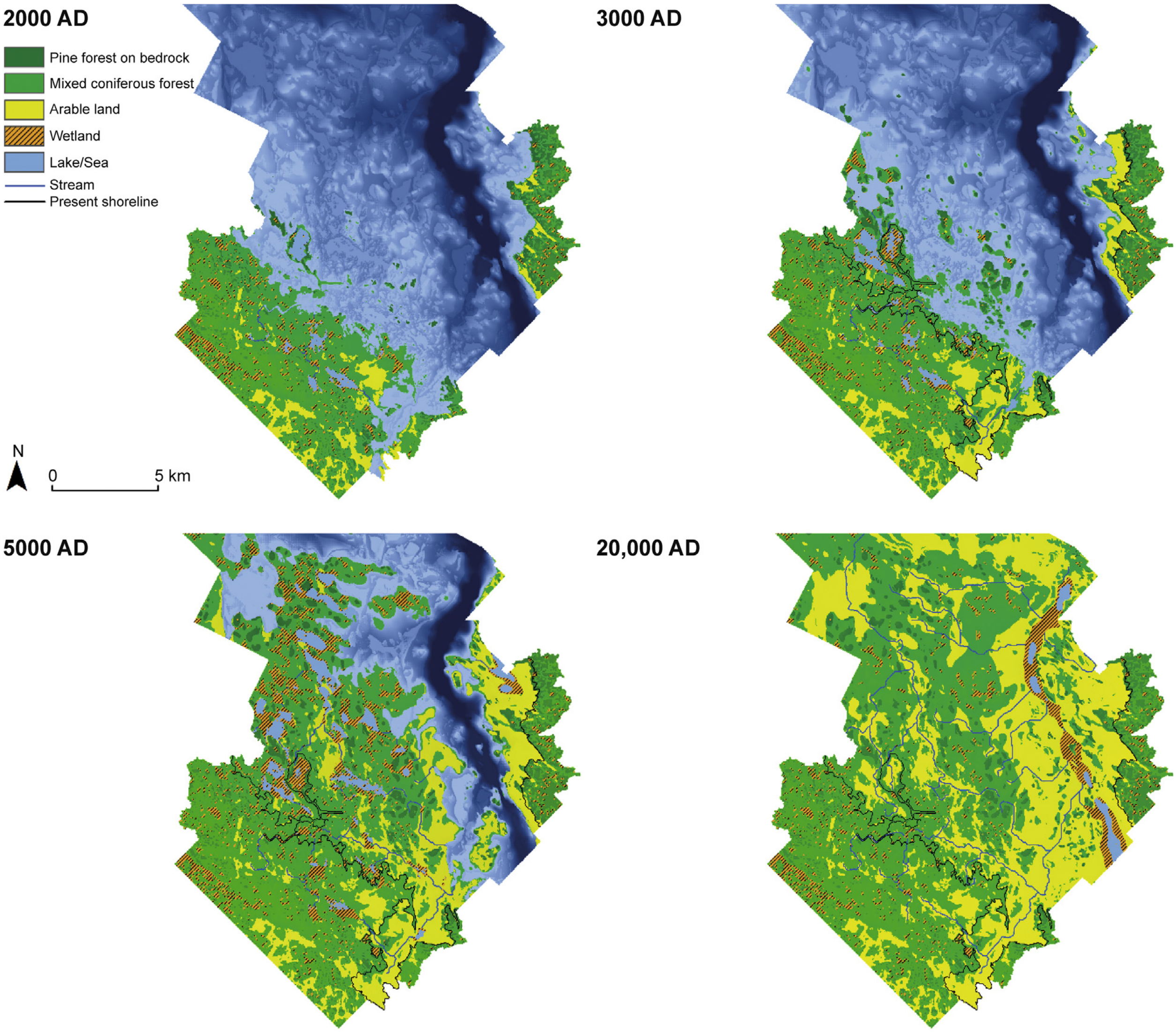

Fig. 3. Landscape succession and ecosystem development shown for 2000 AD, 3000 AD, 5000 AD and 20,000 AD using results from the landscape development model. (SKB, 2014b). This variant of the landscape development shows all areas that can be used for agriculture as arable land (yellow areas on the maps). Under other assumptions regarding future human land-use, some of these areas could be, for instance, forest.

Most of the groundwater potentially carrying radionuclides from the SFR repository is expected to be discharged into a relatively small area (Odén et al., 2013). During the first period after repository closure this area is located in the sea, close to the shoreline. Radionuclides are expected to pass through deep sediments before reaching biologically active soft bottoms and the sea water in the basin. From the primary basin, radionuclides will spread through water exchange with nearby basins, and eventually concentrations will be diluted in the Baltic Sea. After land rise and the development of a lake-mire complex, radionuclides from the repository will pass through deeper sediments (including deep peat) before reaching oxygenated and biologically active surface peat. From the primary discharge area, radionuclides can then reach down-stream lakes or wetland areas through transport via surface and sub-surface water fluxes. The water fluxes on and just below the surface were estimated using hydrological models developed with MIKE SHE (Werner et al., 2013).

Areas in the present and/or future landscape that potentially, at any time during the considered assessment period, could receive radionuclides from the repository via groundwater or surface water are defined as “biosphere objects” in the safety assessment. The biosphere objects are thus the spatial units used to quantitatively evaluate the fate of radionuclides reaching the surface ecosystem in the future Forsmark landscape, and the associated radiation doses, dose rates and risks.

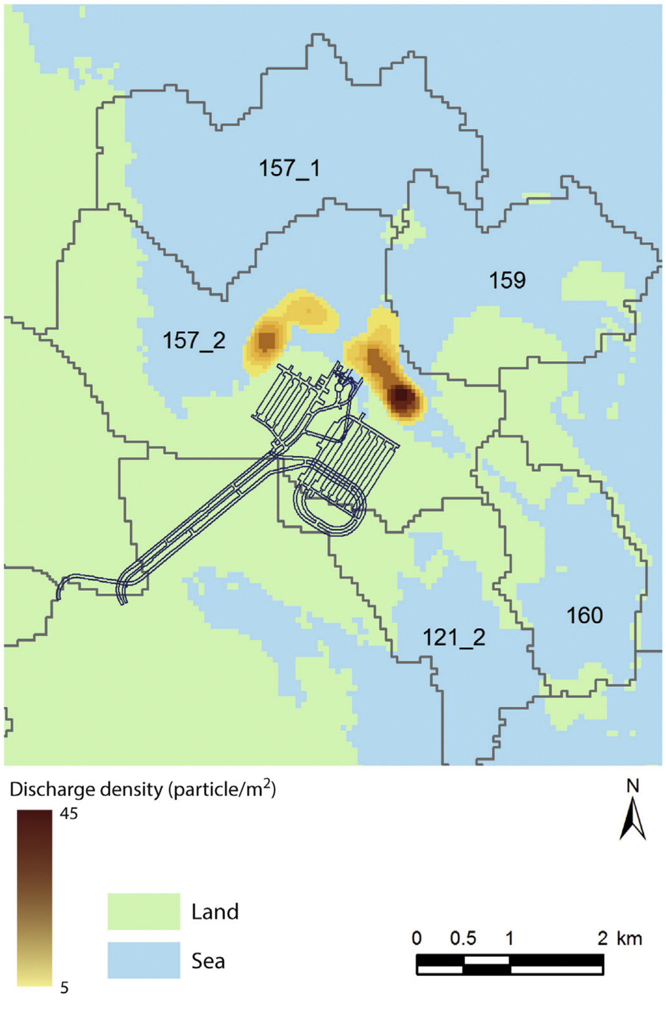

Fig. 4. Densities of simulated discharged non-reactive particles (number of particles per m^2) from SFR obtained with models for 3000 AD. Particles are discharged into roughly the same locations also when the area is terrestrial. The numbers and delineated areas refer to the identified biosphere objects (see text for definition). The indicated areas are the catchment areas of the biosphere objects once they have emerged from the sea (see SKB, 2014b for details).

In the earlier assessment of the planned high-level waste repository at Forsmark (SR-Site), areas for potential radionuclide emergence were more or less likely anywhere in a landscape of 100 km^2 depending on which canister could fail and where the shoreline was situated (Berglund et al., 2013). This shows that it is important for each safety assessment to evaluate discharge from the specific repository and release situation at hand, especially since there is a large difference in effort between analysing many and just one or a few biosphere objects.

2.5. *The radionuclide transport model for surface ecosystems*

Concentrations of radionuclides in environmental media (soil, sediment, water, air and plants) are modelled in a compartment model (Saetre et al., 2013a). The model is the final link in the assessment model chain that calculates radionuclide transport from the repository, through the geosphere to the surface (SKB, 2014e). However, the biosphere part of the model is also used separately to investigate certain assumptions made in the biosphere modelling. Here, the biosphere model is only described briefly. More details of this and other parts of the model can be found in Saetre et al. (2013a) and SKB (2014e).

The model is based on process understanding from the site, incorporating the landscape development of the discharge areas, and has been parameterised primarily based on site data. As the release of individual radionuclides from the repository varied considerably over the assessment period, transport and accumulation in surface ecosystems were calculated using a continuous time-varying release of radionuclides from the geosphere (SKB, 2014e). The calculated environmental concentrations of radionuclides were used to assess exposures of both humans and non-human biota.

A graphical representation of the radionuclide transport model for a single biosphere object is shown in Fig. 5. The model includes an aquatic part and a terrestrial part, which makes it possible to model the radionuclide concentration in environmental media in the changing landscape where the biosphere objects transform from marine to terrestrial ecosystems. The model includes compartments representing the radionuclide inventories in different regolith layers (soils and sediments), water, biota, and the atmosphere. Fluxes of radionuclides between the compartments are linked to mass fluxes of water, gas and solid matter, to transitions between inorganic and organic forms of radionuclides, to diffusion in soil pore water, and to the expansion of mire vegetation. For the objects considered in the present modelling, radionuclides may enter the model domain with groundwater from below, by surface water from other (upstream) objects, and/or through interactions with the atmosphere.

Some important modifications of the previous model used in the assessment of HLW (Avila et al., 2013) were made. Special attention was given to potential storage and subsequent release of C-14 in the identification of model compartments, e.g. organic compartments were included to allow for accumulation of C-14 and other radionuclides in regolith layers of natural ecosystems that can later lead to exposure through cultivation. A new conceptual and numerical model of the atmosphere was developed. It allows separation between near-surface and higher layers (Saetre et al., 2013a), which facilitates better estimates of the leaf uptake of terrestrial plants. The ERICA tool (Brown et al., 2008) used to assess exposure to non-human biota was included in the radionuclide

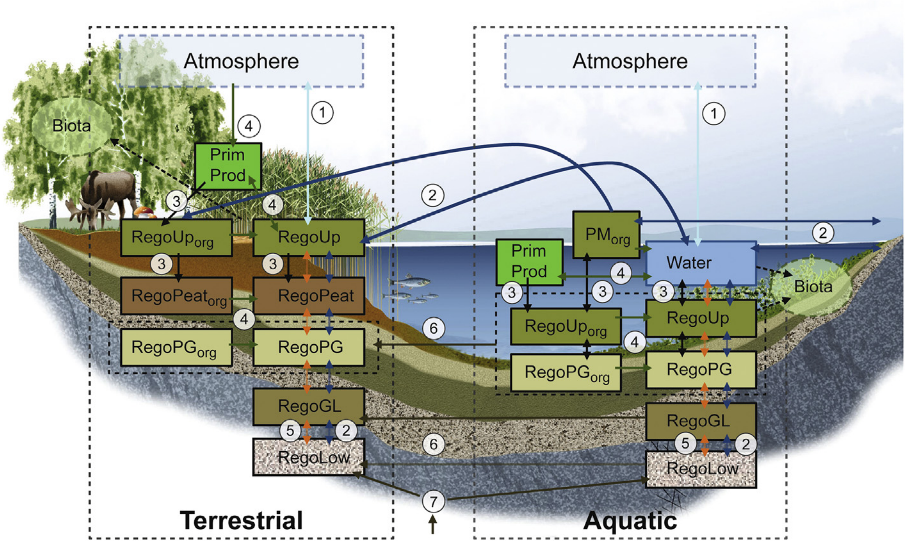

Fig. 5. A graphical representation of the radionuclide transport model used to simulate transport and accumulation in a biosphere object (discharge area) with two natural ecosystems, one terrestrial and one aquatic system (each delimited by thin dotted black lines). Each box in the two ecosystems corresponds to a radionuclide inventory associated with a physical compartment. Arrows represent radionuclide fluxes between compartments and fluxes into and out of the system. Radionuclide fluxes are linked to mass fluxes of gas (1, light blue), water (2, dark blue) and solid matter (3, black), to transitions between inorganic and organic forms of radionuclides (4, green), to diffusion in soil pore water (5, red), and to ingrowth of wetland vegetation (6). Radionuclides from the repository enter the biosphere object in the lower regolith (7). The atmosphere serves as a source and sink of radionuclides (from Saetre et al., 2013a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transport model and implemented directly in the assessment model.

3. Results and discussion

The purpose of the safety assessment is to ensure that human health and the environment are protected from harmful effects of ionising radiation caused by the repository. This is achieved by showing compliance with regulatory requirements, which means that the annual risk of harmful effects after closure must not exceed 10^{-6} (corresponding to approximately 14 μSv year^{-1}) for a representative individual in the group exposed to the greatest annual radioactive dose (SSM, 2008). The protection of the environment, here referred to as non-human biota (NHB), includes the protection of biodiversity and sustainable use of biological resources (SSM, 2008). The regulation does not state dose rate (or risk) constraints for the protection of non-human biota; in the current assessment SKB has applied the screening dose rate of 10 μGy h^{-1} proposed in the ERICA methodology (Beresford et al., 2007; Brown et al., 2008) and the ICRP recommended derived consideration reference levels (DCRLs, ICRP, 2014) when these are lower than the ERICA screening values. The screening dose rate represents a no-effect threshold, above which it is possible that negative effects could occur in some non-human biota populations.

3.1. Dose rates to non-human biota

For each ecosystem, a set of organisms likely to receive the highest exposure were identified. ERICA reference organisms (or slightly modified versions thereof) were used to represent the diversity of species at the site reasonably well. However, a few site-specific organisms were also added to the set of assessed populations (e.g. freshwater microphytobenthos and European otter) to more accurately represent some organism types at the site. The selected organism groups represented the following ecosystem categories: pelagic marine organisms living (or feeding) in the sea water column; benthic marine organisms living on top of or in marine surface sediments in sea ecosystems; pelagic limnic organisms living (or feeding) in the water column of lake and/or stream ecosystems; benthic limnic organisms living on top of or in surface sediments in lake and/or stream ecosystems; and terrestrial organisms living on top of or in surface peat in mire ecosystems.

Results from the main scenario show that dose rates to non-human biota (NHB) are about three orders of magnitude below the screening level (Fig. 6). For NHB, the freshwater ecosystem generally gives the highest dose rates of each variant. Initially, C-14 dominates the dose rates to all organisms, which gives similar dose rates for all organisms, with the highest dose rate to the freshwater bird. However, as C-14 decays (half-life = 5730 years) the dose from C-14 drops significantly; as a result, the bird becomes one of the least exposed organisms, and zooplankton and vascular plants become the most exposed freshwater organism types. Even if the pattern and level of exposure appear similar in the graph, the underlying dominating radionuclides may be quite different between organisms or those living in different habitats. For example, in the freshwater ecosystem, the dose rate to zooplankton is dominated by Pa-231 and later Ni-59, whereas dose rate to vascular plants is dominated by U-238 and later Pu-239. More details on the results for other ecosystems are presented in SKB (2014e).

3.2. Dose to humans

When characterising the most exposed group, physical and biological characteristics of the biosphere objects, human requirements for energy and nutrients, and habits from historical and present societies were considered (Saetre et al., 2013a, 2013b). The potentially most exposed groups were assessed by using four land-use variants that served as credible bounding cases for exposure through a combination of exposure pathways (SKB, 2014d). The land-use variants included in the assessment were: Hunting and gathering (HG) – represents a community using natural ecosystems in the landscape for living space and food; Infield–outland farming (IO) – represents self-sustained agriculture where inland farming of crops and livestock breeding are dependent on hay from wetlands (outland), used as fodder and the manure as organic fertiliser; Draining and cultivating a mire (DM) – represents a self-sustained agriculture in which wetlands are drained and used for agriculture (both crop and fodder production); and Garden plot household (GP) – represents a household that is self-sustained with respect to vegetables and root crops produced through small-scale horticulture. These groups are similar to the findings from the biomass methodology (IAEA, 2003).

When drainage and cultivation of a mire is feasible, the DM land-use variant results in the highest dose, but the difference in the maximum dose between different agriculture based land-use variants is limited (Fig. 7). The dose to HG, who forage natural ecosystems, is within the same order of magnitude during the temperate period. Moreover, HG is the only group for which exposure pathways exist when the sea basin is submerged or when periglacial climate conditions prevail. It can also be noted that fertilization with sea weeds (GP), or fertilization of wetland hay (IO), yields the highest exposure in periods before cultivation of the mire in the discharge area is possible. The highest dose is found in the biosphere object that receives direct discharge of groundwater from the repository, except for a period around 20,000 AD and in periods of periglacial climate conditions when accumulation in a down-stream wetland area results in higher exposure. The total dose increases rapidly when the simulated discharge starts (at 3000 AD), comes to a maximum after the biosphere object has fully emerged from the sea, and then decreases slowly until the onset of the first periglacial period. The dose dominating radionuclide shifts from C-14 to Mo-93, then to Ca-41, and in the end of the assessment period Ni-59 is the main contributor to the annual dose (Fig. 8).

Though the maximum dose is surprisingly stable after 4500 AD, the dynamics of individual dose contributing radionuclides is diverse (Fig. 8). For each radionuclide, the dose curve reflects the combined effect of radioactive decay, retention in barriers, bedrock and regolith layers, transport and dilution by groundwater, as well as uptake by plants and animals and human land-use practices. In previous SKB assessments, dose calculations were based on the assumption that the discharge rate of radionuclides to the biosphere will be approximately constant in time, and that the conversion from release to dose can be sufficiently well represented by a general, or ecosystem specific, dose conversion factor (SKB, 2011). In the present analysis no such assumptions have been made, and a coupled model integrating the whole system is used.

The present simulations show that timing is an important factor, and that retention in regolith layers and other biosphere features may modify the shape of the dose curves significantly. For example, the dose of Mo-93 peaks when the release rate from the geosphere is declining, and Ni-59 doses steadily increase throughout the

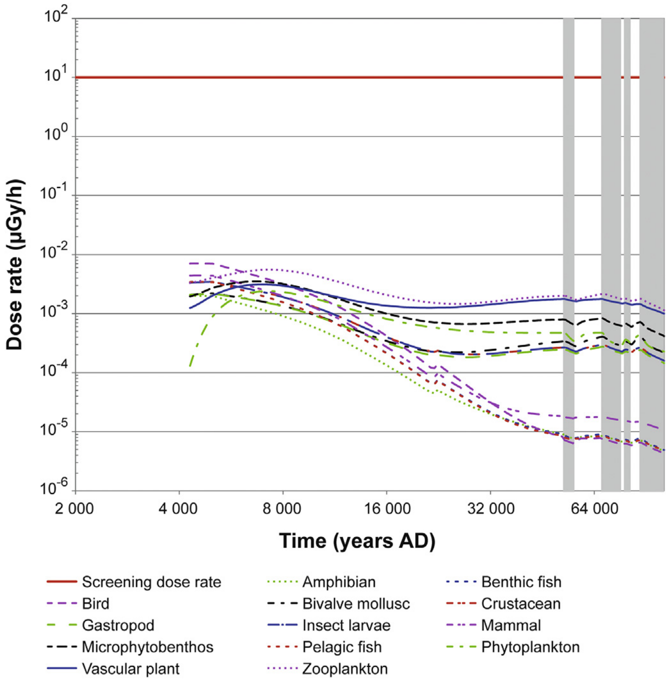

Fig. 6. Dose rates to non-human biota in the freshwater ecosystem for the global warming variant of the main scenario in the safety assessment. Dose rates reached their maximum shortly after the beginning of the assessment (between 4500 and 7300 AD, depending on organism type) as radionuclides from the repository reach the surface environment. Following these peaks, the dose rates decrease quickly as shorter-lived radionuclides decay, and decrease slowly thereafter, as longer-lived radionuclides decay (details in SKB, 2014a).

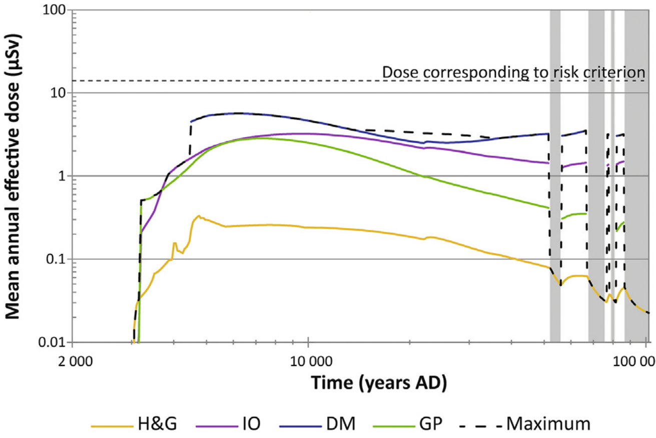

Fig. 7. The annual effective dose to the different exposed groups in biosphere object 157_2 and maximum annual effective dose for one variant of the main scenario. The white areas indicate periods of temperate climatic conditions and the grey shaded areas periglacial conditions with continuous permafrost. (HG – hunters and gatherers, IO – infield-outland farmers, DM – drained-mire farmers, and GP – garden plot household). More results and risk estimates are presented in SKB (2014a).

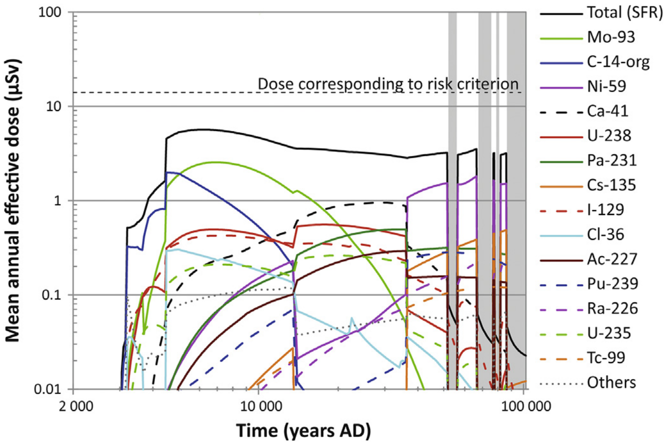

Fig. 8. Arithmetic mean of the annual dose to the most exposed group (maximum dose) for dominating radionuclides. Results are shown for doses from releases from all rock vaults in SFR (cf. Fig. 2) in one variant of the main scenario. The white areas correspond to temperate climatic conditions in the radionuclide transport modelling and the grey shaded areas to periglacial conditions with continuous permafrost. More results and risk estimates are presented in SKB (2014a).

assessment period, although the input rate from the geosphere is fairly constant. Thus, to apply a constant dose conversion factor for all points in time is clearly not a reasonable simplification for radionuclides that do not approach stable stationary concentrations within a narrow time frame.

Furthermore, one can clearly question the rationale for applying a dose conversion factor derived from assumptions of a constant release to radionuclides that have steadily decreasing release rates throughout the assessment period (e.g. U-238). Therefore, we are confident that the coupled geosphere-biosphere model, which accounts for the timing of transport within all system components, has resulted in a significant increase of model coherency as compared to the previous methodology used for HLW (cf. Avila et al., 2010).

The biosphere model simulates transport and accumulation in both aquatic and terrestrial ecosystems that undergo succession, includes more than twenty different biosphere transport processes, accounts for transport between different areas in the landscape, and handles an array of relevant exposure routes to future human populations. With the end results at hand one could argue that the most exposed group can successfully be assessed from just modelling long-term accumulation in a wetland ecosystem. However, such insights can only occur in retrospect, and their validity is obviously constrained to the examined release scenarios, which are rarely known beforehand. Thus, if the release to the biosphere shifts to an earlier stage, other exposure pathways (such as fertilization with sea weeds or hay-making) are likely yielding the maximum doses, and a prolonged release of e.g. Mo-93 would probably have resulted in maximum doses occurring in the downstream area (Fig. 7).

Moreover, for the assessment of periglacial and submerged conditions, when cultivation is not possible, large areas of the landscape and several different ecosystems contribute to exposure. Whereas system understanding relating to the highest exposure can arguably be derived from a much simpler model as discussed by Walke et al. (2015), we are confident that the present biosphere model has a level of detail that is fit for purpose, namely to robustly demonstrate protection of humans and the environment over very long time periods in a heterogeneous landscape going through considerable change.

The dose is below that corresponding to the risk criterion and thus demonstrates safety of SFR under the main scenario. However, the full risk evaluation includes several climate cases and other less probable scenarios; detailed presentations of other climate cases and uncertainty analysis are found in (SKB, 2014b, d).

4. Conclusions

In the SFR assessment, radionuclide concentrations in the environment are modelled from dominating transport pathways in surface ecosystems, and these concentrations are used to assess the protection of both humans and non-human biota. Ingestion of food is the main exposure route for humans, and in the model radionuclide intake is a function of the area of contamination, the production capacity of the land, the cultivation system, human demands for energy and the size of the exposed group. The results from the safety assessment show that the extended SFR repository complies with Swedish regulations of radiation protection, and that the potential dose to humans is within one order of magnitude of the risk criterion. Dose rates to non-human biota are, on the other hand, several orders of magnitude below the screening limit. Hence we conclude with high confidence that by protecting humans the environment is also protected in this case.

Several of the assumptions and simplifications that were relevant and useful when modelling the fate of radionuclides in Forsmark ecosystems in the previous safety assessments of a deep geological repository for HLW were not applicable in the present analysis. This was primarily due to the shorter time scale of relevance for the relatively short-lived LILW waste, the dynamics of the release of radionuclides from the SFR repository, and the properties of radionuclides significantly contributing to the potential dose. The relatively short time also affects the handling of climate variations, and the effects of global warming on present temperate climate conditions was of key interest in the present assessment. The potential discharge from the SFR repository is expected to be confined to one relatively well defined area above the repository. This is in contrast with the assessment of HLW, where climate variations were represented by several repeated glacial cycles, and uncertainty with respect to the location of the source terms, in combination with large scale expected shifts in geohydrology, resulted in a set of equally likely potential discharge areas spread across the Forsmark landscape.

In the present assessment, the modelling of radionuclide transport from the repository, through the geosphere, and to and within the biosphere is fully linked, and external conditions along transport pathways are subject to coordinated spatial and temporal changes. Thus, the development of the landscape and the shifts in climatic conditions affect groundwater-born transport in the geosphere and the biosphere jointly, drive the succession of ecosystems and determine the environmental conditions under which radionuclides may accumulate and cause exposure.

After an initial period, when the area is covered by the sea, the dose resulting from discharging radionuclides is relatively stable over the 100,000-year assessment period. However the dynamics of individual dose contributing radionuclides is diverse and the timing of transport within all system components is an important factor for the pattern of the resulting dose curve. We conclude that the model approach used in this safety assessment has resulted in a significant increase of model coherency compared to earlier assessments, and that the biosphere model has a level of detail that is fit for purpose, namely to robustly demonstrate protection of humans and the environment over long time periods.

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