SSI Rapport

SSI report

2003:14

ANDERS WÖRMAN

Exchange processes at geosphere-biosphere interface

Current SKB approach and example of coupled hydrological-ecological approach

Statens strålskyddsinstitut

Swedish Radiation Protection Authority

AUTHOR/ FÖRFATTARE: Anders Wörman*
* Department of Biometry and Technology, Swedish University of Agricultural Sciences (SLU)

SSI rapport: 2003:14
september 2003
ISSN 0282-4434

DEPARTMENT/ AVDELNING: Waste Management & Environmental Protection/ Avd. för avfall och miljö

TITLE/ TITEL: Exchange processes at geosphere-biosphere interface. Current SKB approach and example of coupled hydrological-ecological approach.

SUMMARY: The design of the repository for final disposal of spent nuclear fuel proposed by SKB is based on a multi barrier system, in which the geosphere and biosphere are the utmost barrier surrounding the engineer barriers. This report briefly reviews the current approach taken by SKB to account for hydrological and ecological processes at the geosphere-biosphere interface (GBI) and their future plans in this area. A simple analysis was performed to shift the focus of performance assessment involving geosphere-biosphere interface modelling from the very simplistic assumption that the quaternary sediments are bypassed to one in which a more detailed model for sub-surface flows is included.

This study indicated that, for many assumed ecosystem descriptions, the presence of the GBI leads to lower maximum doses to individual humans compared to a case when the GBI is neglected. This effect is due to the additional "barrier" offered by the GBI. The main exposure pathways were assumed to occur through the food web. However, particularly the leakage on land through the stream-network and lakes can lead to higher doses due to ecosystem interaction with arable land. A scenario that gives particularly long duration of doses occurs due to land rise and with the transformation of the former bay and lake bed sediments into agricultural land. This effect is due to the significant retention or "accumulation" in aquatic sediment, which causes high activities to build up with time. Particularly, in combination with changing conditions in climate, humans life-style or geographic conditions (land rise, deforestation, etc.) doses to individual humans can be large

SAMMANFATTNING: Konstruktionen av slutförvaret av det radioaktiva avfallet som föreslås av SKB baseras på ett flerbarriärsystem, vilket ytterst omges av geosfären och biosfären. Denna rapport granskar SKB´s aktuella metoder att ta hänsyn till hydrologiska och ekologiska processer i kontaktzonen mellan geosfär och biosfär, samt deras fortsatta planer i detta område. En enkel analys genomfördes för att kristiskt testa säkerhetsanalysernas modellering av geosfär-biosfärsprocesser. Speciellt undersöktes relevansen av de förenklade antagandena om att radionuklider obehindrat passerar kvartära avlagringar genom att införa en mer detaljerad beskrivning av den ytnära hydrologin.

Undersökningen indikerar, för många antagna ekosystemfunktioner, att närvaron av kontaktzonen mellan geosfär och biosfär ofta sänker de maximalt uppnådda doserna till enskilda människor jämfört med om zonen försummas. Detta beror på den "extra barriäreffekt" som erhålls av kvartära avlagringar. De huvudsakliga spridningsvägarna antogs ske genom näringskedjan. Högre doser kunde dock uppnås under vissa förutsättningar, speciellt på grund av läckage till grunda vattendrag och sjösediment samt en vidare spridning till odlingsbar mark. Ett scenario som gav särskilt höga doser var när en kontaminerad sjöbotten omvandlades till odlingsbar mark genom en successiv landhöjning. Denna effekt beror på den väsentliga ackumulering av miljöstörande substanser som sker i akvatiska sediment, vilket innebär att höga doser kan byggas upp över en lång tid. Speciellt, i kombination med förändrade klimatvillkor, mänskliga aktiviteter eller andra geografiska villkor (landhöjning, minskad vegetation, etc.) kan innebära höga doser till människan.

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Contents

1 Introduction

One of the concerns about the SKB programme for finalizing the final disposal of high-level nuclear waste is how various parts of the safety analysis are coupled to each other. Such a coupling can be important if there is a feedback between different parts of the system or in order to ensure a reliable analysis of the "interface-processes".

This report briefly comments upon the current approach taken by SKB to account for hydrological and ecological processes at the geosphere-biosphere interface (GBI) and their future plans in this area. Section 2 contains a general description of the geosphere-biosphere interface and sections, 3 and 4, contain a review of SKB´s current approach to treating processes at the geosphere-biosphere interface both from a perspective of measuring (site investigation) programme and formal assessment in safety analyses.

The report also describes in sections 5 and 6 the result of an introductory study performed by SSI on processes at the GBI and their impact on ecology. In addition to the author of this report, the study was perfomed by Ryk Klos, Aleksandra Sciences, Björn Dverstorp, SSI, and Shulan Xu, SSI (Wörman et al., 2003).

In the recent analyses performed to date in the Swedish nuclear waste management programme, the link between geosphere and the biosphere has been treated in a simplified manner (Bergström, et al., 1999). Radionuclides have been assumed to flow directly from the bedrock into the water column of coastal ecosystems with no interaction between the bedrock and the overlying quaternary sediments. The study described in sections 5 – 6 focuses on the geosphere-biosphere interface, i.e. quaternary deposits, provide different discharge pathways to surface ecosystems and how this affects the risk assessment. The importance of considering processes in the GBI and their dependence on underlying factors are analysed in the context both of residence times of radionuclides in different system components as well as doses to humans related to pathways through arable land, pasture, streams and lakes.

2 Geosphere-biosphere interface and exchange processes

A usual method for predicting stresses in ecosystems is to use compartment models for contaminant transfer between various species or well-defined biotic, hydrological or geochemical components. Environmental stresses are defined in terms of external loads of certain key elements such as phosphorus or heavy metals and focus is on the circulation of the element between biotic compartments. In safety assessments of the final nuclear waste repository the loads are expressed in terms of contaminant flows and radiological doses obtained from transport models representing the deeper geology ("geosphere") surrounding the repository and the engineered barrier system. Important factors for the analysis are the release rates of radionuclides through the engineered barriers, transport through the host rock in which the repository is placed and retention as well as transport at the geosphere-biosphere interface (GBI). The term GBI is here used to denote the quaternary and more recent deposits, which overly the crystalline bedrock. The transport and redistribution of radionuclides on different biotic compartments at the GBI is governed by a range of complex processes, such as accumulation due to geochemical processes, interaction between surface waters and ground waters and uptake of radionuclides in biota.

There are a number of possible pathways and several transport mechanisms with importance to the transfer rate of solute elements at the GBI as well as the spatial distribution of exchange rates. Essential factors are briefly mentioned here:

- *Diagenetic processes in bottom sediments of oceans, lakes and stream*

govern the retention of solute elements that pass through sediments in streams and lakes draining the catchment area in which the repository is placed.

The water saturated parts of the quaternary deposits host many biotic processes with relevance for accumulation of solute elements as well as for the pathway selection in ecosystems. Diagenetic processes in lake or Sea sediments are normally classified in terms of deposition of sediment, re-suspension/erosion, sorption, bioturbation (and biotic irrigation) and mineralisation (Berner, 1980). There are also several chemical reactions that are depth dependent due to the fact that there are gradients in oxygen (redox-potential) and organic content. The increasing oxygen content towards the interface/bed surface leads to a higher mobility of metals (or radionuclides) towards the interface, whereas this variation is counteracted by the higher organic content in surficial sediments (Salomon and Förstner, 1984).

The corresponding processes also exist in streams and other drainage systems (wetlands, lakes).

- *Hydrological/Hydraulic interactions between surface (lakes, streams) and groundwater in catchments*

arise due to the spatial variation in hydraulic potential on different spatial scales. Particularly, in flowing water there is a hydraulic interaction between the surface water and the sub-surface because of the variation in hydraulic potential in the landscape that associates with friction losses along a streamline through the watershed. In a lake, the re- or discharge areas are governed by regional flow pattern and redistribution of contaminated sediments can occur due to erosion and deposition patterns. A process referred to as focusing lead to accumulation of contaminants below the wave base in a central part of the lake.

In streams, the exchange of solutes from the surface water to the sub-surface (often called the hyporheic zone) can occur in a meandering river that has different flow directions in relation to the direction of the groundwater flow (Wroblicky, 1995) and in streams with spatially varying slope (Harvey and Bencala, 1993; Castro and Hornberger, 1991). A flow can also be induced in the hyporheic zone by its deflection against irregularities of the bed surface of biotic (Huettel et al., 1996) or hydro-mechanical origin (Elliott and Brooks, a and b; Runkel et al, 1996a and b) or obstacles like tree branches or stones. Superimposed on these exchange patterns comes the exchange caused by the regional topography of the watershed with hills and valleys. All together, the exchange pattern can be complicated and it is furthermore complicated by heterogeneities of the hydraulic conductivity of the quaternary deposits and underlying bedrock.

- *Root systems of trees and plants*

can mediate the exchange of water and solute elements from the ground to the surface. Even if the dominating exchange of water at the GBI is probably due to infiltration and discharge (hydraulic potential), pathways directly to biota may have a special importance to dose assessments.

- *Regional hydrological systems with special retention characteristics,*

like wetlands and lakes, can significantly prolong the export of solute elements from land to the ocean. Indirectly, this retention has implication to the solute exposure to terrestrial and limnological ecosystems. Retention characteristics and residence times of wetlands and lakes are important for the overall residence times of radionuclides in the GBI.

- *Human activities*

like groundwater policy and mining could potentially have a severe implication to the exchange processes at the GBI. Tunnel constructions affect the groundwater movements in large areas and could function as drains for regional areas.

- *Global changes*

cause time variable conditions that potentially could be very important from a risk perspective. For instance, with time it is possible that former sea sediments form parts of the continents due to land rise or sea level changes.

3 SKB´s current approach for treating exchange processes at the GBI

Documents with relevance to SKB´s current approach for treating processes at the geosphere-biosphere interface include 1) the safety assessment of SFR (SKB, 2001c), 2) SR 97 safety assessment exercise (SKB, 1999a and c; Lindgren and Lindström, 1999; Bergström et al., 1999), 3) the methodology for the site investigation programme for the spent nuclear fuel waste repository (SKB, 2001a), and 4) R&D programmes (SKB, 1998; SKB 2001b). Two aspects are addressed in this section; i) aspects covered by the field investigation programmes and that potentially can be addressed in future PAs and ii) PA methodology and modelling procedures that are actually developed and applied in reported safety assessments.

Site investigation programme

SKB suggests that the following factors is covered in the site investigation (SKB, 2000; SKB 2002)

- Rock type distribution
- Location of fracture zones and water flow
- Statistical description of fractures
- Bedrock stresses and mechanical properties
- Heat conduction properties of bedrock
- statistical properties of hydraulic conductivity
- natural hydraulic gradients on repository level
- Groundwater chemistry: redox potential, salinity, Fe(II)-content, sulfide, pH, organic content, colloid content, ammonium content, calcium content, magnesium content, radon content and radium content
- statistical distribution of matrix diffusivity and matrix porosity
- description of ecosystems and other ground surface conditions

The above factors have relevance to exchange processes at the biosphere-geosphere interface. Thus, the extensive mapping of the current state of the biosphere and quaternary deposits that is proposed by SKB and currently executed at regions close to Forsmark and Oskarshamn, will most probably lead to an improved understanding of the functioning of the GBI such as pathway formation and effects in ecosystems. Consistent with the site investigation programme, a more pronounced focus on the GBI is announced in recent R&D documents (SKB 2001b) and to some extent applied in the renewed safety assessment for SFR (SKB, 2001d).

An important factor for the characterisation of processes at the GBI, which is not thoroughly discussed in the site investigation programmes (SKB, 2000; SKB 2001a), is the spatial resolution of measurements needed to provide a sufficient basis for process descriptions and risk assessments. The surface hydrological systems are tremendously spatially heterogeneous with respect to most properties, like hydraulic conductivity, biota and geochemistry. Further, there is a marked seasonal variation in most factors, particularly in our tempered climate. In order to facilitate use of the data in PA, the spatial and temporal sampling distribution must be planned with respect to the spatial and temporal heterogeneity. The measuring programme seems not to be formally linked with a modelling procedure that can be utilised in PAs that address the severe problems of heterogeneity. One important task of the measuring programme, discussed in the next sub-section, is to provide relevant statistical information needed in a risk assessment.

Due to the rapid change of the biosphere and quaternary deposits on a geological time frame, there is an additional need to reconsider how the data can be utilised for long-term analyses. Because of this and other reasons, it would be important to show clear relationships between the site investigation programme and the modelling context in which the data is eventually utilised. Similar critics were presented in the SKI / SSI joint review of the SR 97 safety exercise for a lacking relationship between the site investigation and the performance assessment (SKI /SSI, 2001). Models may not be completely governing for the planning processes, because of the simplifications and limitations often associated with mathematical models, but should provide essential guidance for critical decisions on type of measuring techniques, temporal and spatial sampling frequency, type of data etceteras.

Because discharge of groundwater will pass through aquatic sediments in streams, lakes or the Baltic Sea bed, diagenetic processes are vital for the exchange of radionuclides from sub-surface aquifers to surface waters. One may suspect that the site investigation programme is not fully adequate for a sufficient coverage of relevant factors for retention and transport of radionuclides in aquatic sediments. To an extent this limitation is understandable, because there are inherent difficulties to account for the large number of essential transport properties of aquatic sediments, like sorption properties, topography, biotic activity, geochemical/geological status and evolution (due to depth and deposition condition), as well as the spatial heterogeneity of these properties. However, it would be desirable if the rationales behind this part of the site investigation programme were more clearly declared.

Further, the site investigation programme should be related to on-going, independent environmental monitoring programmes in Sweden, e.g. the national programme initiated by the Swedish Environmental Protection Agency, and other independent investigations. For instance, there have been extensive investigations of sediments, particularly in the Baltic Sea, forests, streams, lakes and land in a large number of university projects. Not much is discussed in the site investigation programme (SKB, 2000) on how these independent data bases (e.g. http://info1.ma.slu.se/db.html) can be accessed and utilised, or how the programme complements the results of other investigations in an appropriate manner.

Modelling procedures

The performance assessment comprises both a general framework used to assess the overall "risk" associated with a leakage scenario and underlying detailed models that deals with specific physical, chemical or biological issues ranging from canister failure and transport of radionuclides to climatic changes and ecological effects. The overall risk framework has a general significance for coupling of the detailed models and the possible problems that may arise in such a coupling.

The approach to evaluate risk applied in SR 97 was relatively simplistic in that the main probabilistic analysis concerns flow properties of the geosphere, whereas other probabilities are represented from assumed (simple) functions that to some extent are arbitrary without underlying analysis or data (SKB, 1999c). An essential simplification in this approach is the negligence of conditional probabilities (how the probability distribution of one system component depends on the behaviour of a related system components). The limitation of the outcome space for an individual event given a specific position in an outcome tree, implies that the conditional probability of the individual event is generally higher than the unconditional probability for that event. Since, conditional probabilities are strongly associated with the coupling of different biological, geochemical and hydrological processes, the risk approach of SR 97 can be interpreted as having a "weak focus" on coupling *all* processes and system components in an overall risk perspective.

Consistently, the geosphere-biosphere interface (given a certain definition discussed in sections 2 and 5) is not treated in all (expected or suspected) relevant details in either the radionuclide transport models (Lindgren and Lindström, 1999) or in the dose assessment models (Bergström et al., 1999). The estimation of doses to individual humans is based on the assumption that radionuclides are released in coastal water without a direct accumulation in bed sediments (unless recirculated through the coastal water) by diagenetic interactions (Klos and Wilmot, 2002). The analyses of radionuclide migration do not comprise a complete pathway from the respository to individual humans and this is one implication of neglecting the conditional probabilities in the risk analysis.

Before SR 97 the SKB research programme did not contain much research on the hydrological interaction between groundwater and surface water and the relevance of biological and geochemical processes at the GBI. More recent safety assessments comprises an even more simplistic risk concept than applied in SR 97 (SKB, 2001c and d), but do, however, regardless of this limitation include studies with a more clear focus on processes in the GBI. The studies underlying the safety assessment of SFR describe a more holistic view on hydro-geological modelling and, especially, the coupling between surface and sub-surface hydrology is recognised in terms of surface topography and quaternary deposits (SKB, 2001d; Holmén and Stigsson, 2001). In this manner, the surface topography defines essential boundary conditions that drive the sub-surface flow on the watershed scale, also in the bedrock at the depth of the repository. However, the hydro-geological model used to represent this boundary effect due to the GBI is not the same as used for the analysis of radionuclide transport in the geosphere (SKB, 2001 c, p 105) and this regrettably introduces concerns about fragmentation of the approach and insufficient completeness in the overall risk assessment.

The R&D programme of 2001 includes a discussion on the importance of a formal risk analysis and includes many aspects of the GBI. These planned developments are discussed below.

4 SKB R&D programme with relevance to GBI

The SKB research and development programme of 2001 (SKB, 2001b) contains several positive new contributions. Here follows a list of factors that most likely will improve the manner by which processes at the GBI will be accounted for in the safety assessment:

- A probabilistic development of the performance assessment is proposed. This will significantly strengthen the coupling between previously separated components in the analysis of radionuclides that are transported through the geosphere into the biosphere.

- The R&D report suggests an improved mapping of surface water hydrology (mapping of discharge and infiltration areas, GIS, hydrological and geochemical field studies). This is the basis for development of the understanding of how radionuclides are distributed in the biosphere and with what rates the exchange at the GBI occurs.

- Development of models for particle associated transport. This is of utmost importance to the understanding of the transport of sorbing elements, like radionuclides, in all surface water systems. The accumulation and retention of contaminants in sediment is the primary mechanism that retards the export of solute elements from land to the ocean.

- Mires (and bogs) are given special attention – studies of their hydrology is proposed. A particularly high degree of retention can be expected in certain aquatic systems with a high availability to solid surfaces on which sorption of radionuclides can occur.

- Sediment deposits and diagenetic processes are given special attention. There are also suggested studies on providing historical evidences of erosion events and transport of Chernobyl Cs in the GBI. These studies should be helpful in improving our understanding of the transport of radionuclides. It should be noted, however, that the scientific community has already produced huge amounts of results on these issues and that further "in-depth" studies should be based on already existing knowledge. Especially, the short-term perspective (1 – 15 years) on transport of Cs in the biosphere (surface waters and sediments) is well covered (Nyffeler, et al., 1986; Comans et al., 1991; Comans and Hockley, 1992; Wieland et al., 1993; Monte, 1995, 1996; Meili and Wörman, 1996; Smith et al., 2000).

The various factors included in the safety analysis are suggested to be included in a formal risk analysis (SKB, 2001a). However, there are no suggested detailed plans on how the risk analysis should be developed in order to account for complete transport pathways and different scenarios. Exactly how sub-surface and surface hydrology should be coupled and linkage with ecological effects is left to be defined in future R&D activities.

5 Modelling exercise of the impact of GBI processes on coupling of sub-surface and surface hydrology and ecological effects

A minor research project initiated by SSI comprised a modelling exercise of the coupling between sub-surface and surface hydrology on a watershed/regional scale. The purpose was to investigate for specific geological, hydrological and ecological conditions to what extent processes at the GBI are important for ecological effects, particularly doses to individual humans.

A schematic geological setting was assumed in which the final destination for radionuclides released in groundwater is a coastal bay ecosystem or a lake receiving inflow from a terrestrial catchment system, respectively (Fig. 1). Two ecological models were used in the study and the corresponding simulation exercises are referred to as case 1 and 2. Case 1 is based on the ecosystem model of Bergström, *et al.*, 1999 and the case 2 model is BIOMASS Example Reference Biosphere 2B (IAEA, 2002, a, b and c). In the first model case, release to the "biosphere" model takes place by groundwater filtration through quaternary sediments below the sea-bed of a bay and a contribution which has emerged in the surface hydrology and subsequently flows into the bay. In the latter model case, release takes place to bed sediments in a lake and the superficial deposits along the catchment drainage system. Thus, there is a secondary pathway to the lake via the surface hydrology. The complexity in exposure pathways is considered in the latter model by accounting also for terrestrial ecosystems as well as a more complex food web.

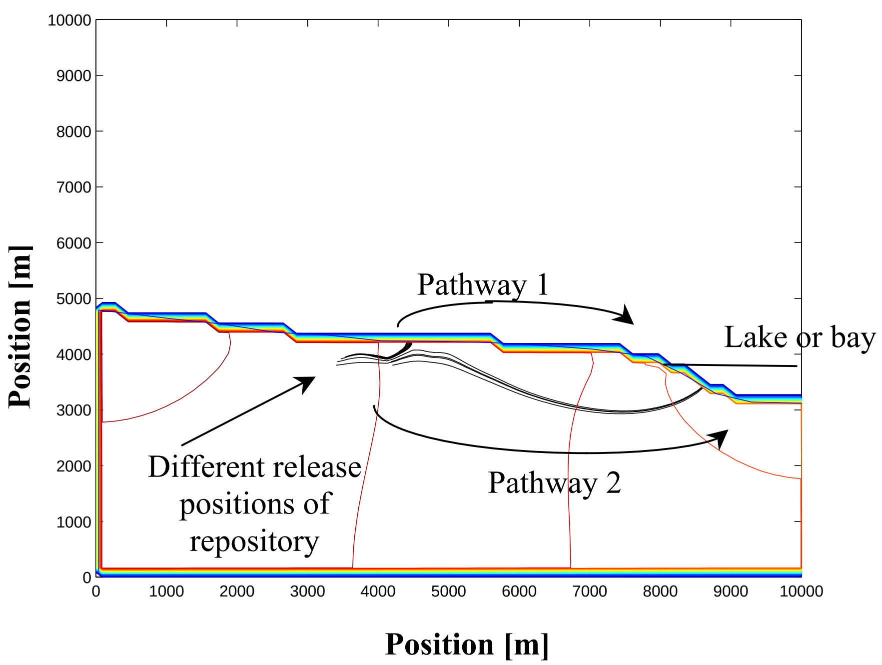


Fig 1: Geometry and equi-potential curves. Black curves represent 10 trajectory paths from different release points on a depth varying between 240 – 440 m. Note that these pathways are clustered, which means that the individual trajectories do not reveal in this figure. Water surface is aligned with the ground surface on this scale. A lake is placed to the right.

In the bedrock – quaternary sediment system we distinguish two hydrological pathways. Pathway 1 goes through bedrock, quaternary sediment layers to surface hydrological systems and continue through streams and rivers to the lake/bay water column on the right hand side of Fig 1. Pathway 2 passes through the bedrock directly to the lake/bay sediment. The sub-surface hydrology is simulated in a two-dimensional plane (vertical and longitudinal directions) based on stationary Darcy flow.

Particles are released at random positions to represent leakage of radionuclides from a hypothetical repository that is placed at a depth of 240-440 m about 5 km from a lake. On top of the bedrock there is a 20-meter thick quaternary sediment layer both on land and beneath the lake/bay (Fig. 1). The particles are released at different positions along the circumference of an ellipse with axes 400 and 200 m and a pulse release (Dirac δ-function) of the example radionuclide ^{135}Cs is assumed. In this way, we represent significant uncertainties in the transport pathways and the result is a distribution of pathways with different hydrological and geochemical characteristics. The modelling techniques are defined more thoroughly by Wörman et al. (2003).

6 Simulation Results

6.1 Pathways and transport analysis

The hydrological simulations indicate that surface topography can cause local circulation cells that extend from the ground surface down to the level of the repository. This implies that there is probability of establishment of a pathway through the quaternary sediment layers into surface water and, further, into the lake or bay water (pathway 1 in Figure 1). In this calculation example, 19% of migrating radionuclides escaped through this pathway, but this proportion is highly dependent on the depth in bedrock, surface topography and location of the repository in relation to the lake. Presence of heterogeneities in rock conductivity is another important factor.

The remaining fraction of radionuclides (81%) migrated along a deeper pathway to the lake bottom sediment (pathway 2 in Figure 1). Depending on what type of bottom area the discharge merges into, radionuclides may accumulate in bottom sediments (deposition areas) or be advected into the water column through erosion bottoms. The accumulation process of Caesium in deposition areas has been well studied, for instance, by Comans et al. (1991), Wieland et al., (1993), Meili and Wörman (1996) and Smith et al. (2000). There is also an internal turnover of radionuclides that lead to a reaccumulation in deposition areas. In the subsequent example of ecosystem modelling it is assumed that 50% of the discharge goes directly into the lake water column.

Table 2 shows the average residence time for water and ^{135}Cs in different zones of the hydrosphere. The average residence time for water in the bedrock (both pathways) is 1438 years, which is much higher than for the quaternary sediment layer for which the time is only 35 years. The difference is smaller, however, than expected from the Darcy velocity due to the much lower porosity of the bedrock (water flows relatively fast in a few fractures). Furthermore, the difference in residence time is reversed for ^{135}Cs because of the high retardation factor in quaternary sediments (Table 1). The residence time in the deep lake sediments is exceptionally long for ^{135}Cs (485,000 years) due to the slow flow velocity below the lake and a high retardation factor.

For each of the pathways shown in Fig. 1 there is a distribution of residence times in the subsurface, i.e. a distribution of times when migrating radionuclides contribute actively to exposure pathways in the biosphere and to doses to individual humans. These residence time distributions were used as input for estimation of ecosystem responses as described in section 6.2.

6.2 Ecosystem Responses

The effect of the GBI was investigated with the coast model (case 1) mentioned in section 4 for two calculation variants; one in which the quaternary deposits were eliminated and all radionuclides that reached the biosphere were instantaneously put in the coastal zone and one variant with account taken to transport processes in the GBI. 500MBq ^{135}Cs is released instantaneously in both variants. No pathways through terrestrial ecosystem were considered in this analysis.

From the results of case 1 in Fig. 2 we can see that the total activity in the coastal zone will be much higher when the GBI is taken into consideration. The average radioactivity represented by the radionuclides accumulated in the top sediment for the case with GBI was

Table 1: Retardation coefficients for different media. Z = matrix "depth" in bedrock, n = porosity, h = fracture aperture in bedrock, ρ = rock density, ξ = area reduction factor for the water exchange between a stream and the hyporheic zone, P = wetted parameter of a stream, V_z = exchange velocity for water between a stream and the hyporheic zone, T = residence time of inert solutes (water) in the hyporheic zone, A = cross-sectional area of stream, K_D = ratio of particulate solute mass to dissolved solute mass in soil (concentrations defined as mass per a certain, e.g. bulk, volume) , K_D = partition coefficient defined as adsorbed solute mass per mass of rock divided by dissolved solute mass per volume of water and K_B = ratio of particulate solute mass to dissolved solute mass in the hyporheic zone of streams.

Medium	**Retardation factor, *R***	**References**
Bedrock	$2Z\frac{n}{h}(1+\frac{\rho}{n}K_d)$	[Xu and Wörman, 1998]
Soil and lake sediments	$\left(1+K_d\right)$	[Kutilek, Nielsen, 1994; Berner, 1980]
Streams and rivers	$\frac{1}{2}\left(1+K_B\right)\frac{\xi P V_z T}{A})$	[Wörman et al., 2002]

Table 2: Mean residence times in different zones in the hydrosphere for the current calculation example.

	Average water residence time [years]	**Average Caesium (^{135}Cs) residence time [years]**
Average through bedrock all pathways	1438	15,819
Through quaternary sediment layer to stream drainage system	35	17,716
Through river to lake or bay	0.033	427
Through bottom sediments (20 m) of lake	968	485,300
Path 1: Bedrock and quaternary sediment layer	2,495	44,754
Path 1: Bedrock, quaternary sediment layer and river to lake	2,495	45,181
Path 2: Bedrock, sediments and lake	2,166	498,470

800 times higher than without consideration of GBI. The accumulated radionuclides represent a potential risk for man depending on what exposure pathways are assumed to develop with land rise or other time dependent factors (see comparison below). The peak value of the dose to individual humans is about 6 times higher for the case when GBI was omitted than with account taken to GBI (Fig. 3), supporting the claim that neglect of the GBI is a cautious modelling assumption. However, the time of duration with a relative higher biosphere dose is much longer for the latter case. Furthermore, this result takes no consideration of land development.

Results from the Terrestrial – aquatic ecosystem model of case 2 are shown in Fig. 4. The total activity released was about 500 MBq. In this model scenario, the dose to humans becomes slightly higher due to the GBI than when GBI is neglected. This is because of the terrestrial interactions of ecosystems and surface hydrology.

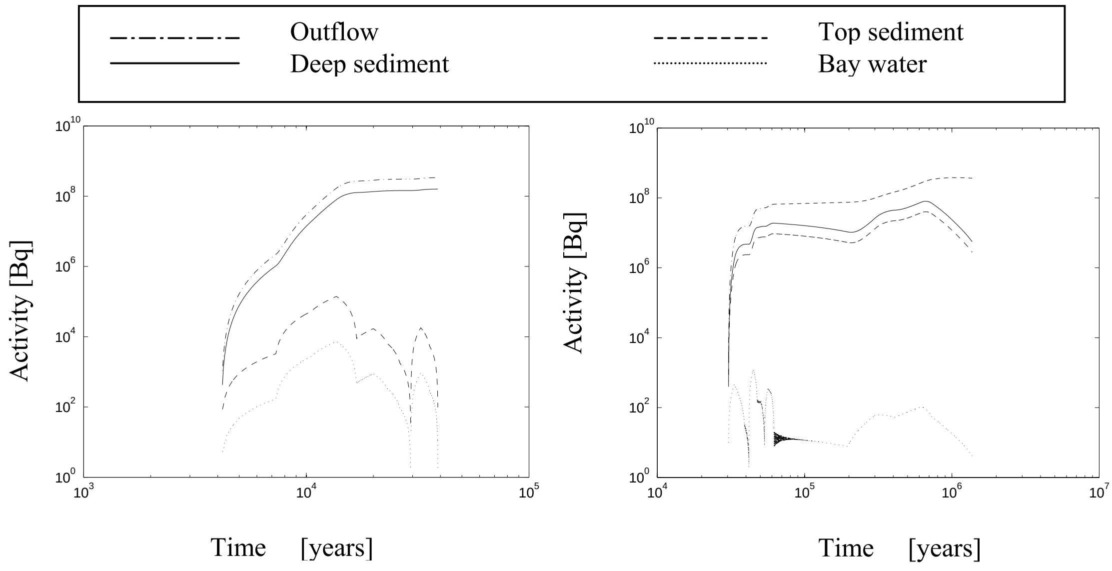


Fig. 2 Radionuclide content in Bq accumulated in various compartments as function of time for the coastal ecosystem model used in SR 97 (case 1). On the left-hand side is the result when GBI is neglected and on the right-hand side is the result with account taken to GBI, in which radionuclides are transport into the bay through two pathways, pathway 1b and pathway 2 as shown in Fig. 1.

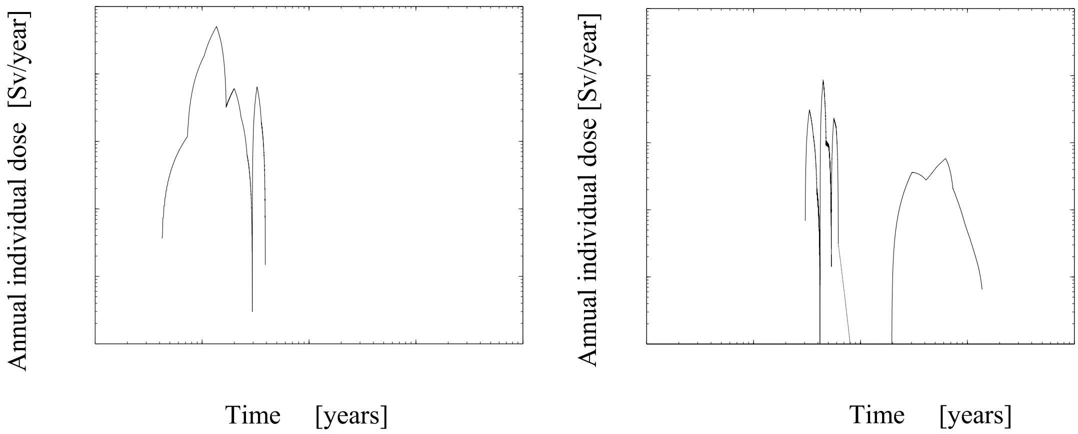


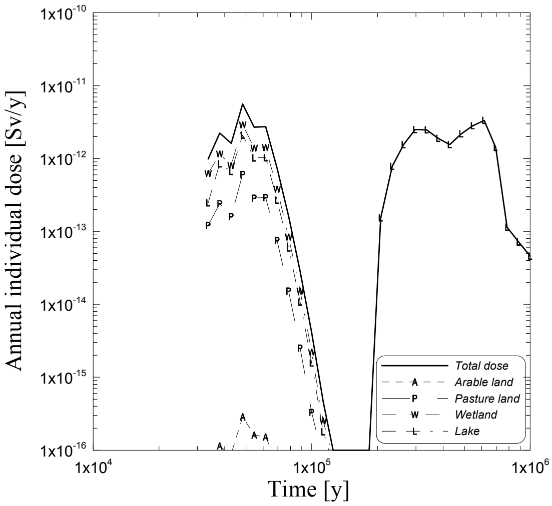
Fig. 3 Dose rate to individual humans caused by release of radionuclide the hypothetical repository as function of time according to the coast model (case 1). The diagram on left-hand side reflects the results without GBI and to the right are the results with account taken to GBI.

With no interaction with the quaternary deposits there is effectively a direct release to lake or bay water. Some of the exposure pathways due to, for instance, fish in streams, livestock water consumption and human water consumption would be inactive and give zero dose. When interaction with the quaternary sediments is taken into account, all pathways are active.

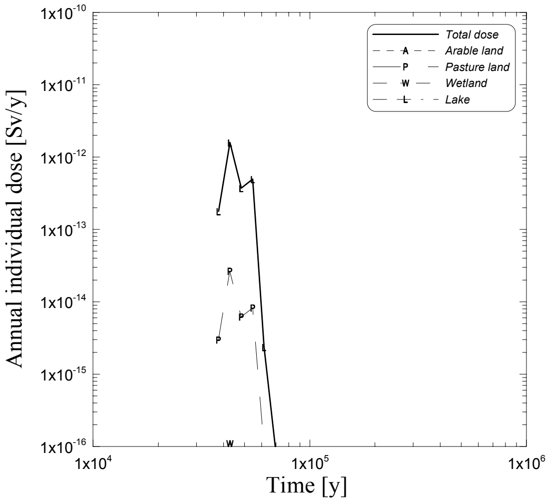
Doses from the woodland ecosystem dominate slightly those from the other ecosystems. As with the coastal ecosystem, the duration of the doses is longer than in the case of direct release to the ecosystem models. In contrast to the coastal model, accumulation in the terrestrial biosphere leads to higher doses, contradicting the assumption of conservatism placed on the direct release scenarios used by SKB (1999b).

To investigate the effects of landscape evolution a further simulation scenario was carried out using the ecosystem model arable land. With land rise, the lake eventually dries out and the accumulated activity in the sediments becomes distributed throughout the saturated, deep soil and rooting soil zones. This change occurs at around 600 years. All arable and pasture land pathways where then evaluated with equivalent climate conditions based on an initial inventory of ^{135}Cs in the system. There was no aquatic component to this model and no further radionuclide input to the system. The results in Fig 4. indicate that the doses arising from agriculture on such a system would be dominated by the arable pathways (at least for this radionuclide). The doses are rather lower than in the direct release scenarios but the duration of the dose at fairly constant levels is prolonged.

With account to GBI



GBI neglected



With account to GBI and lake sediment converted to farmland after 600 years

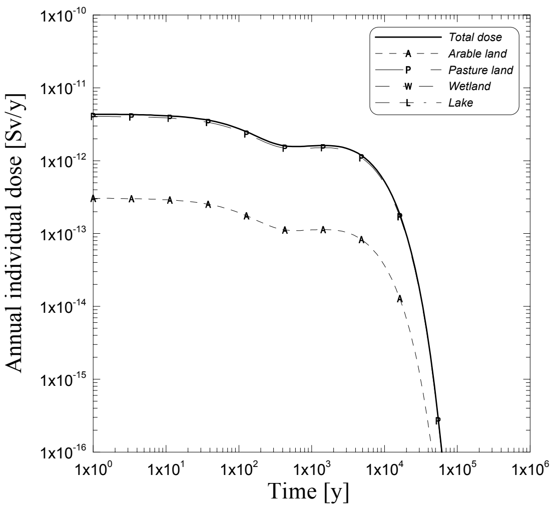


Fig. 4 Doses to individual humans as resulting from the Terrestrial – aquatic ecosystem model. Contribution from arable land, pasture land, wetland and lake ecosystem is marked in the figures.

7 Conclusions

Migration pathways from a repository for spent nuclear fuel that is placed in crystalline bedrock may significantly depend on the presence of quaternary deposits. For certain realistic assumptions, the residence time for radionuclides in quaternary deposits can dominate over those in the bedrock. Also the migration time in surface hydrological system cam play a role, especially if the interaction of terrestrial and aquatic ecosystem is taken into account.

The SKB research programme and safety assessment approach generally do not include aspects of the geosphere-biosphere interface. Analyses of radionuclide transport in the geosphere (GBI) are performed to a large degree regardless of surface hydrological conditions and ecological effect studies (e.g. estimates of doses to humans) are not mathematically coupled to the geosphere modelling. The R&D programme of SKB, however, includes a more clear focus on GBI and there are also discussions on a framework for integrated previously partly fragmented models; a formal risk analyses is announced.

This study indicated that, for many assumed ecosystem descriptions, the GBI leads to lower maximum doses to individual humans. This effect is due to the additional "barrier" offered by the GBI. The main exposure pathways taken into account are related to the food web. However, particularly the leakage on land through the stream-network can lead to higher doses due to ecosystem interaction with arable land. A scenario that gives particularly long duration doses occurs due to land rise and with the transformation of the former bay and lake bed sediments into agricultural land. This effect can be considered to be an "accumulation" effect in which high activities build up with time. Particularly, in combination with changing conditions in humans life-style of geographic conditions (land rise, climatic change etc.) doses to individual humans can be large.

This work has shifted the focus of performance assessment geosphere-biosphere interface modelling from the very simplistic assumption that the quaternary sediments are bypassed to one in which a more detailed model for sub-surface flows is included. Results here indicate the potential for accumulation in the surface ecosystems to be important in determining radiological risks at far future times. With improvements in detailed models of flow in quaternary material, linked to deeper bedrock flow and transport, the emphasis should shift to more realistic interpretations of the mixing between meteoric water and groundwater. An improved representation of these processes will enhance our understanding of the biosphere functions and provide a better basis for evaluating environmental impact and radiological dose consequences.

References

Bergström, U., Nordlinder, S., Aggeryd, I., 1999. “Models for dose assessments – Modules for various biosphere types”, SKB Technical Report TR-99-14.

Berner, R.A. 1980. Early Diagenesis, Princeton Univ. Press, Princeton, N.J., New Jersey, USA.

Castro, N.M., Hornberger, G.H., 1991, Surface-Subsurface Water Interactions in an Alluviated Mountain Stream Channel, Water Res. Res., 27(7), 1613-1621.

Comans, R. N. J. and Hockley, D. E. (1992). Kinetics of cesium sorption on illite.*Geochemica et Cosmochimica Acta*, Vol. 56, pp. 1157-1164.

Comans, R. N. J., Haller, M. and Preter, P. D. (1991). Sorption of cesium on illite: Non-equilibrium behaviour and reversibility. *Geochemica et Cosmochimica Acta*, Vol. 55, pp. 433-440.

Elliott, A.H., Brooks, N.H., 1997a, "Transfer of nonsorbing solutes to a streambed with bed forms: Theory", Water Res. Res., 33(1), 123-136.

Elliott, A.H., Brooks, N.H., 1997b, "Transfer of nonsorbing solutes to a streambed with bed forms: Laboratory experiments", Water Res. Res., 33(1), 137-151.

Harvey, J., Bencala, K.E., 1993, The effect of Streambed Topography on Surface-Subsurface Water Exchange in Mountain Catchments, Water Resour. Res., 29(1), 89-98.

Holmén, J.G., Stigsson, M., 2001. “modelling of future hydrogeological conditions at SFR Forsmark”, SKB-report R-01-02, Swedish Nuclear Watse Mangement Co, Stockholm.

Huettel, M., Ziebis, W., Forster, S., 1996. Flow-induced uptake of particulate matter in permeable sediments, Limnol. Oceanogr., 41(2), 309-322.Lerman, A., Mackenzie, F.T., Garrels, R.M., 1975. "modelling of geochemical cycles: Phosphorus as an example", geol.Soc.Amer.Mem., 142, 205-218.

IAEA, 2002a. “Reference Biospheres for Solid Radioactive Waste Disposal, Volume I: Overview, Final report of BIOMASS Theme 1”, IAEA, Vienna, Austria, in press.

IAEA, 2002b. “Reference Biospheres for Solid Radioactive Waste Disposal, Volume II: Methodology, Final report of BIOMASS Theme 1”, IAEA, Vienna, in press.

IAEA, 2002c. “Reference Biospheres for Solid Radioactive Waste Disposal, Volume III: Example Reference Biospheres, Final report of BIOMASS Theme 1”, IAEA, Vienna, in press.

Klos, R., Wilmot, R., 2002. ”Review of Projecty SAFE: Comments on biosphere conceptual model description and risk assessment methodology”, SSI report 2002:17, ISSN 0282-4434.

Kutılek, M., Nielsen, D. R., 1994, Soil Hydrology, Catena Verlag, Cremlingen-Destedt, Germany.

Lindgren, M., Lindström, F., 1999. “Radionuclide transport calculations”, SKB Technical Report TR-99-23.

Meili, M., Wörman, A, 1996, "Desorption and diffusion of episodic pollutants in sediments: a 3-phase model applied to Chernobyl ^{137}Cs" J. Applied Geochemistry, 11, 311-316.

Monte, L. 1995, "Evaluation of radionuclide transfer functions from drainage basins of fresh water systems", J. Environ.Radioactivity, 26, 71-82.

Monte, L., 1996, "Analysis of models assessing the radionuclide migration from catchments to water bodies", Helth Physics, 70(2), 227-237.

Nyffeler, U. P., Santschi, P. H. and Li, Y-H. (1986). The relevance of scavenging kinetics to modelling of sediment-water interactions in natural waters. *Limnol. Oceanogr*. Vol. 31, No. 2, pp. 277-292.

Runkel, R.L., Bencala, K.E., Broshers, R.E., Chapra, S.C., 1996a, "Reactive solute transport in streams - 1. Development of an equilibrium-based model", Water Resour. Res., 32(2), pp 409-418.

Runkel, R.L., Bencala, K.E., Broshers, R.E., Chapra, S.C., 1996b, "Reactive solute transport in streams - 2. Simulation of a pH modification experiment", Water Resour. Res., 32(2), pp 419-430.

Salomons, W., Förstner, U., 1984, Metals in the Hydrocycle, Springer-Verlag.

SKB, 1999a. "SR 97 - Processer i förvarets utveckling", SKB report, Swedish Nuclear Watse Mangement Co, Stockholm, ISBN 91-972810-2-6.

SKB, 1999b. Deep repository for spent fuel SR 97 — Post closure safety. Swedish Nuclear Fuel and Waste Management Co, Stockholm, SKB Technical report TR-99-06, Swedish Nuclear Watse Mangement Co, Stockholm.

SKB, 1999c. "SR 97 – Post-closure safety: Deep repository for spent nuclear fuel, Main report Volume I and Volume II", Swedish Nuclear Watse Mangement Co, Stockholm.

SKB, 2000. "Geovetenskapligt inriktat program för undersökning och utvärdering av platser för djupförvaret", SKB report R-00-30, Swedish Nuclear Watse Mangement Co, Stockholm, ISSN 1402-3091.

SKB, 2001a. "Platsundersökningar: Undersökninsgmetoder och generellt genomförandeprogram", SKB report R-01-10, Swedish Nuclear Watse Mangement Co, Stockholm, ISSN 1402-3091.

SKB, 2001b. "FUD-program 2001 – Program för forskning, utveckling och demonstration av metoder för hantering och slutförvar av kärnavfall", SKB report, Swedish Nuclear Watse Mangement Co, Stockholm, ISSN 1104-8395.

SKB, 2001c. "Project SAFE: Scenario and system analysis", SKB report R-01-13.

SKB, 2001d. "SFR1, SSR: Version 1.0 / SAFE – main report, Chapter 5", SKB working document 2001-06-30, Swedish Nuclear Watse Mangement Co, Stockholm.

SKB, 2002. "Execution programme for the initial site investigations at Forsmark", SKB report P-02-03, Swedish Nuclear Watse Mangement Co, Stockholm.

SKB, 1998. "FUD-program 1998 – Kärnkraftavfallets behandling och slutförvaring: Program för forskning samt utveckling och demonstration av inkapsling och geoligisk djupförvaring", SKB report, Swedish Nuclear Watse Mangement Co, Stockholm, ISSN 1104-8395.

SKI / SSI, 2001. "SKI´s and SSI´s joint review of SKB´s safety assessment report, SR 97", SKI Report 01:04, SSI-report 2001:03.

Smith JT, Comans RNJ, Ireland DG, et al.2000. ”Experimental and in situ study of radiocaesium transfer across the sediment-water interface and mobility in lake sediments” APPL GEOCHEM 15 (6): 833-848 JUL 2000

Wieland, E, Santchi, P.H., Höhener, P., Sturm, M., 1993, "Scavening of Chernobyl ^{137}Cs in lake Sempach, Switzerland", Geochemica et Cosmochimica Acta, 57, 2959-2979.

Wroblicky, G.J., 1995. ´"Numerical Modeling of Stream-groundwater interactions, near-stream flowpaths, and hyporheic zone hydrodynamics of two first-order mountain stream-aquifer systems", M.S. thesis, University of New Mexico, Alberquerque, USA.

Wörman, A., 1998. "Analytical solution and time scale for transport of reacting solutes in rivers and streams", Water Resources Research, 34(10), 2703-2716.

Wörman, A., Dverstorp, B., Klos, Ryk, Xu, S., 2003. "Role of the Bio- and Geosphere Interface on Migration Pathways for Radionuclides and Ecological Effects", 2003 International High-Level Radioactive Waste Management Conference, March 30 – April 2, 2003, Las Vegas, Nevada, U.S.A.

Wörman, A., Packman, A., Jonsson, K., Johansson, H., 2002. "Effect of Flow-Induced Exchange in Hyporheic Zones on Longitudinal Transport of Solutes in Streams and Rivers" Water Resources Research, 38(1), 2:1-15.

SSI-rapporter 2003
SSI reports 2003

2003:01 Avfall och miljö vid de kärntekniska anläggningarna; tillsynsrapport 2001
Avdelningen för avfall och miljö.
Monica Persson et.al.

2003:02 Stråldoser vid användning av torvbränsle i stora anläggningar
Avdelning för beredskap och miljöövervakning.
Hans Möre och Lynn Marie Hubbard. 80 SEK

2003:03 UV-strålning och underlag för bedömning av befolkningsdos från solarier i en storstadsregion
Avdelning för beredskap och miljöövervakning.
Björn Nilsson, Björn Närlundh och Ulf Wester. 70 SEK

2003:04 Enkätundersökning av entreprenörers inställning till strålning och strålskyddsutbildning vid de svenska kärnkraftverken
Avdelning för personal- och patientstrålskydd
Ingela Thimgren 60 SEK

2003:05 Radiofarmakaterapier i Sverige – kartläggning över metoder
Avdelning för personal- och patientstrålskydd
Helene Jönsson 60 SEK

2003:06 Säkerhets och strålskyddsläget vid de svenska kärnkraftverken 2002

2003:07 Mätning av naturlig radioaktivitet i dricksvatten. Test av mätmetoder och resultat av en pilotundersökning
Avdelning för beredskap och miljöövervakning.
Inger Östergren, Rolf Falk, Lars Mjönes och Britt-Marie Ek 70 SEK

2003:08 Optisk strålning strålskydd
Avdelning för beredskap och miljöövervakning.
Anders Glansholm 70 SEK

2003:09 Årlig kontroll av diagnostisk röntgenutrustning för medicinskt bruk – en utredning av kontrollverksamheten
Avdelning för personal- och patientstrålskydd
Anja Almén och Torsten Cederlund 70 SEK

2003:10 Förändring av stråldoser till patienter vid övergång från konventionell till digital, filmlös teknik vid röntgenundersökning av grovtarm och njurar Slutrapport SSI-projekt P 933
Avdelning för personal- och patientstrålskydd
Börje Sjöholm och Jan Persliden 60 SEK

2003:11 AMBER and Ecolego Intercomparisons Using Calculations from SR97
Avdelningen för avfall och miljö
Gemensam SKI och SSI rapport

2003:12 Analysis of Critical Issues in Biosphere Assessment Modelling and Site Investigation
Avdelningen för avfall och miljö
M. J. Egan, M. C. Thorne, R.H. Little and R.F. Pasco 60 SEK

2003:13 Personalstrålskydd inom kärnkraftindustrin under 2002
Avdelning för personal- och patientstrålskydd
Stig Erixon, Peter Hofvander, Ingemar Lund, Lars Malmqvist, Ingela Thimgren, Hanna Ölander Gür 60 SEK

2003:14 Exchange processes at geosphere-biosphere interface. Current SKB approach and example of coupled hydrological-ecological approach
Avdelningen för avfall och miljö
Anders Wörman 60 SEK

SSI Rapport

STATENS STRÅLSKYDDSINSTITUT, SSI, är central tillsynsmyndighet på strålskyddsområdet. Myndighetens verksamhetsidé är att verka för ett gott strålskydd för människor och miljö nu och i framtiden.

SSI är ansvarig myndighet för det av riksdagen beslutade miljömålet *Säker strålmiljö*.

SSI sätter gränser för stråldoser till allmänheten och för dem som arbetar med strålning, utfärdar föreskrifter och kontrollerar att de efterlevs. Myndigheten inspekterar, informerar, utbildar och ger råd för att öka kunskaperna om strålning. SSI bedriver också egen forskning och stöder forskning vid universitet och högskolor.

SSI håller beredskap dygnet runt mot olyckor med strålning. En tidig varning om olyckor fås genom svenska och utländska mätstationer och genom internationella varnings- och informationssystem.

SSI medverkar i det internationella strålskyddssamarbetet och bidrar därigenom till förbättringar av strålskyddet i främst Baltikum och Ryssland.

Myndigheten har idag ca 110 anställda och är beläget i Stockholm.

THE SWEDISH RADIATION PROTECTION AUTHORITY (SSI) is the government regulatory authority for radiation protection. Its task is to secure good radiation protection for people and the environment both today and in the future.

The Swedish parliament has appointed SSI to be in charge of the implementation of its environmental quality objective *Säker strålmiljö* ("A Safe Radiation Environment").

SSI sets radiation dose limits for the public and for workers exposed to radiation and regulates many other matters dealing with radiation. Compliance with the regulations is ensured through inspections.

SSI also provides information, education, and advice, carries out its own research and administers external research projects.

SSI maintains an around-the-clock preparedness for radiation accidents. Early warning is provided by Swedish and foreign monitoring stations and by international alarm and information systems.

The Authority collaborates with many national and international radiation protection endeavours. It actively supports the on-going improvements of radiation protection in Estonia, Latvia, Lithuania, and Russia.

SSI has about 110 employees and is located in Stockholm.

Statens strålskyddsinstitut
Swedish Radiation Protection Authority

Adress: Statens strålskyddsinstitut; S-171 16 Stockholm;
Besöksadress: Karolinska sjukhusets område, Hus Z 5.
Telefon: 08-729 71 00, Fax: 08-729 71 08
Address: Swedish Radiation Protection Authority;
SE-171 16 Stockholm; Sweden
Telephone: + 46 8-729 71 00, Fax: + 46 8-729 71 08
www.ssi.se