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PAPER

Simplified representative models for long-term flow and advective transport in fractured crystalline bedrock

Joel E. Geier[1] · Georg A. Lindgren[2,3] · Chin-Fu Tsang[4,5]

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Abstract

Simplified representative models (SRMs) of the hydrogeological system at radioactive-waste repository sites are presented and demonstrated to give useful predictions of the key hydrogeological factors affecting long-term safety. The SRM is constructed from complex site-descriptive models, which have been developed to be consistent with detailed site information and data from short-term (with duration of days, weeks, up to months) field experiments, by keeping elements that are important for long-term predictions into thousands of years and simplifying features of less importance. The simplified approach relies only on fundamental hydrogeological principles and the mathematics can be kept relatively simple. The purpose of SRM is to provide a means of verifying predictions from complex numerical models, with an approach that is easy to evaluate and allows transparent evaluation of factors influencing long-term results. The approach is applied to evaluations of sites for two repositories in fractured crystalline bedrock in Sweden: one for spent nuclear fuel rod assemblies and one for waste with lower levels of radioactivity. The results indicate that the SRMs are able to yield results similar to those of calculations based on much more complex models. Further, the approach allows an evaluation of additional sources of uncertainty that are difficult or expensive to conduct with the complex models. These capabilities make SRMs a very useful and transparent tool for regulatory review.

Keywords Radioactive waste · Crystalline rocks · Fractured rocks · Waste disposal · Sweden

Introduction

Motivation

Sparsely fractured crystalline bedrock is the focus of plans for radioactive-waste disposal in several countries, including Finland where construction has started on a facility for permanent internment of spent nuclear fuel in granitic gneiss, and Sweden where plans for a similar facility in granite are under regulatory review (Posiva 2012; SKB 2011). In both countries, facilities for permanent disposal of low- and intermediate level radioactive waste, in the same geological environment, are already in operation.

Prediction of groundwater flow and contaminant transport in such environments is inherently uncertain due to the irregular connectivity of fractures in the bedrock, on scales that cannot be characterized completely. This uncertainty is commonly dealt with by means of stochastic models based on the statistical discrete-fracture network (DFN) concept (Long et al. 1982). Practical computational limits on the scale of DFN models lead to a need for upscaling to alternative representations such as channel-network representations (Moreno and Neretnieks 1993) or continuum representations including multiple-interacting continua (Schwartz 2012) or equivalent continuous porous medium (ECPM) models (Selroos et al. 2002; Selroos and Follin 2014). Upscaling from a DFN model to a continuum representation involves simplifications and assumptions including the question of whether a continuum is valid for a chosen grid scale (Long et al. 1982; National Research Council 1996; Jackson et al. 2000).

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✉ Joel E. Geier
clearwater@peak.org

[1] Clearwater Hardrock Consulting, 38566 Hwy 99W, Corvallis, OR 97330, USA
[2] Swedish Radiation Safety Authority, SE-171 16 Stockholm, Sweden
[3] Present address: Kemakta Konsult AB, SE-112 93 Stockholm, Sweden
[4] Lawrence Berkeley National Laboratory, Earth Sciences Division, 1 Cyclotron Road, Berkeley, CA 94720, USA
[5] Uppsala University, Institute for Geosciences, Villavägen 16, SE-752 36 Uppsala, Sweden

These models are also complex, incorporating many assumptions and parameters, not all of which are directly derivable from site data or observations; thus, they are often built on a chain of interpretations and analyses of site data. From a regulatory standpoint, this makes them difficult to review both regarding sensitivities to key assumptions and errors in representation. In order to give confidence in the accuracy and robustness of results from these models, supplementary analyses using simpler and/or alternative representations of the system are often needed. In principle, benchmarking of complex models with alternative elaborate models is a good way to review a model's trustworthiness. In practice, however, simpler representations can have a role to play as outlined in the following.

Purpose of simplified representative models

This paper describes some characteristics of hydrogeological simplified representative models and their applications to regulatory review of facilities for permanent storage of radioactive waste, specifically at a site located in fractured granitic rock in the Fennoscandian shield in Sweden. Simplified representations are used to conduct long-term predictive calculations and to explore the effects of plausible ranges of properties for the main components of the site-descriptive models.

The term "simplified representative models" (SRMs) is used here because the models are inferred from the relatively complex site-descriptive models that were constructed from, and calibrated to (or at least shown to be consistent with) a large multi-disciplinary geoscientific dataset. Preference is given to representative values of hydraulic properties and other parameters, but conservative values may be used for some components in order to simplify the analysis. The SRMs used here consist of simplified representations of the key hydrogeological features of direct relevance to long-term calculations into thousands of years, while neglecting features that may be needed to match, for example, short-term site-characterization field tests. The purpose of these SRMs is to provide a transparent approach for evaluating long-term effects of the main components of the hydrogeological system, and of the associated uncertainty in the properties of those components. The approach is simple enough that it does not require any specific software to implement, but can be applied using a variety of calculation tools such as spreadsheets or open-source scripting languages (as used here), depending on which tools are most readily accessible for the analysis.

From a regulatory perspective, complex hydrogeological numerical models and their predictions can be difficult to check. Code verification exercises typically are based on much simpler model configurations than the situations for which predictions are needed. Data for prediction/validation exercises are often of short durations for practical reasons and may not be sensitive to all of the key components of the hydrogeological system—for example, for the site considered here, pumping and monitoring intervals for hydraulic interference tests were located for practical reasons mainly in the relatively conductive features (fracture zones), giving limited resolution for the intervening, sparsely fractured bedrock. Hence, there is a need for independent, transparent means of checking that the predictions of these complex models are trustworthy and adequately bound the possible range of behaviors.

The aforementioned discussions are illustrated in Fig. 1, which shows on the left-hand side all the site characterization activities producing data and information that enter into the construction of a numerical implementation of a complex hydrogeological site-descriptive model, which is then subject to short-term confirmatory or validation testing. The complex numerical model thus developed is then applied to long-term prediction and analysis of uncertainties with evaluation of model variants. On the other hand, the SRM is developed from the complex site-descriptive model by retaining elements that have direct relevance to long-term predictions, but with simplifications of details wherever possible. Simplifications can be motivated either because the details have no significant impact on long-term results, or because ignoring them leads to more conservative predictions of risk. The focus of SRM is to evaluate radionuclide early arrival and arrival of the main radionuclide plume, as well as bounding ranges of flow through the waste storage vaults or canister deposition holes.

If both the complex models and the SRM have been developed correctly, the SRM should reproduce complex model predictions and uncertainty analyses and this gives considerable confidence in the validity of the complex model. Further, because of the simplicity built into the SRM, parameter sensitivity and variants evaluation will be more transparent and may unveil deeper insights. The capabilities of confirming predictions of complex models and more transparent evaluation of parameter and variant sensitivities are of major importance from the view of regulatory agencies which have the responsibility of reviewing complex models used by waste-storage-implementation organizations.

The approach follows on a previous application of simple models to scope ranges of groundwater flux and transport resistance (i.e. potential for retardation of radionuclides by matrix diffusion in the bedrock) for hypothetical repositories for spent nuclear fuel, at eight different sites in crystalline rock in Sweden (Dverstorp et al. 1996). That application considered simplified representations of a discharge path consisting of sparsely fractured bedrock and a relatively conductive fractured zone extending from repository depth to the ground surface. Two highly idealized representations of the sparsely fractured bedrock were considered: (1) as an equivalent porous medium with uniform hydraulic conductivity, or (2) as a single, through going discrete fracture that connects directly from the repository to the nearest deterministic conductive

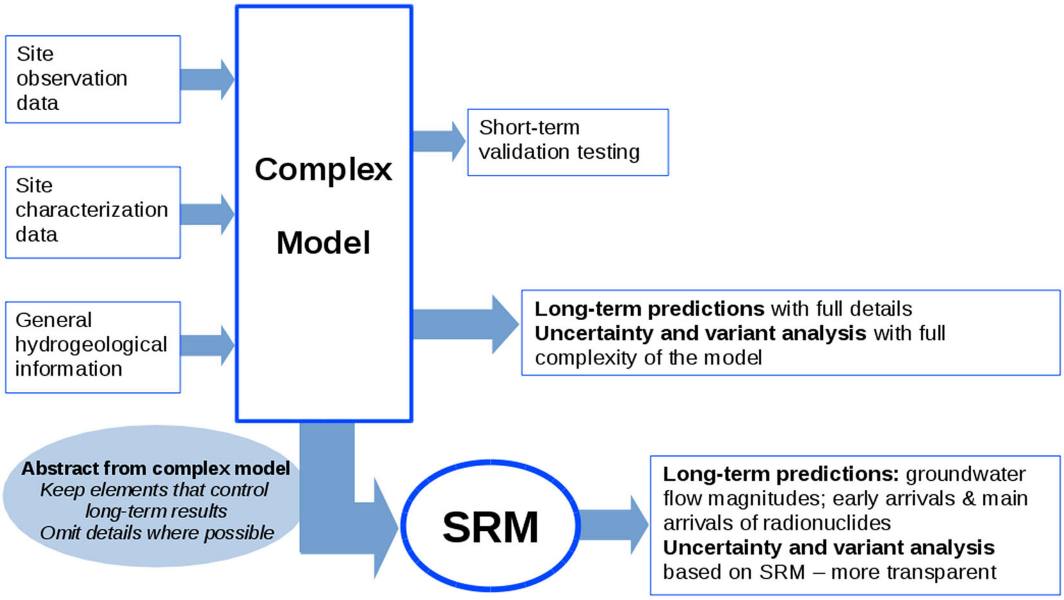

Fig. 1 Conceptual relationship between a complex hydrogeological model and a simplified representative model (SRM)

zone. The study was shown to be valuable for bounding analysis in safety assessment. The ranges of groundwater flux and transport resistance calculated by the simple models were found to bound the range of values calculated by more complex, calibrated site models based on alternative conceptual approaches (stochastic continuum and DFN).

However, further development of the simple approach by Dverstorp et al. (1996) is needed to (1) more clearly define the SRM approach and provide additional justification of its validity, (2) to reduce the ranges of parameters used and avoid excessive conservativism in the bounding analysis, and (3) to clarify the connections and comparisons to more complex models and demonstrate more transparent and insightful evaluation of key assumptions using the SRM. These are the objectives of the present paper.

With a focus on early tracer arrival and transport of the main part of tracers (rather than the later tracer concentration tails), the SRMs in the present work are chosen to be based on a binary division between relatively conductive fractured zones that are treated as deterministic features in the site-descriptive model, and the more sparsely fractured bedrock between those features. They are assumed to be composed of a series of flow segments, through which flow will go one after another from the surface recharge zone into the subsurface, to the repository, and up to the discharge zone. For each flow segment, a highly simplified representation of the sparsely fractured bedrock is developed that captures the important features of the more complex calibrated model. For the present effort, each of the flow segments is represented by one or several one-dimensional (1D) flow conductors with the flow driven by a difference in hydraulic head. Parameters used for each flow segment will be carefully developed from site data and observations, together with a study of the complex model.

This is applied firstly to evaluate groundwater flows through the planned spent nuclear fuel (SNF) repository located at Forsmark and compare the results with those from a prior safety analysis by the Swedish Nuclear Fuel and Waste Management Co. (SKB). Secondly, the method is applied to the proposed expansion of a low- and intermediate-level waste (LILW) repository at the same site, and the results are compared with a corresponding prior safety analysis (SKB 2015). The SRM approach employed relies only on fundamental hydrogeological principles and the mathematics are simple, yet yields results that are similar to those of calculations based on much more complex models, and thus help to confirm and provide confidence for the complex models.

The next section gives an introductory description of the hydrogeological characteristics of the Forsmark site which was chosen for this study, and then a brief summary of the repository concepts used at this site. This is followed by descriptions of the SRM component models that were developed for each of the flow segments and applied for two different types of radioactive waste repositories, for SNF and LILW respectively, at the Forsmark site.

Context and background

Hydrogeological characteristics of the Forsmark site

The Forsmark site is located in Östhammar municipality in northern Uppland, Sweden, along the present-day Baltic coast (Fig. 2). A LILW repository is already in operation at a depth of 70–140 m below the seabed, about 1.5 km offshore. In addition, a SNF repository has been proposed to be constructed just inland from this at a depth of about 450 m (SKB 2011).

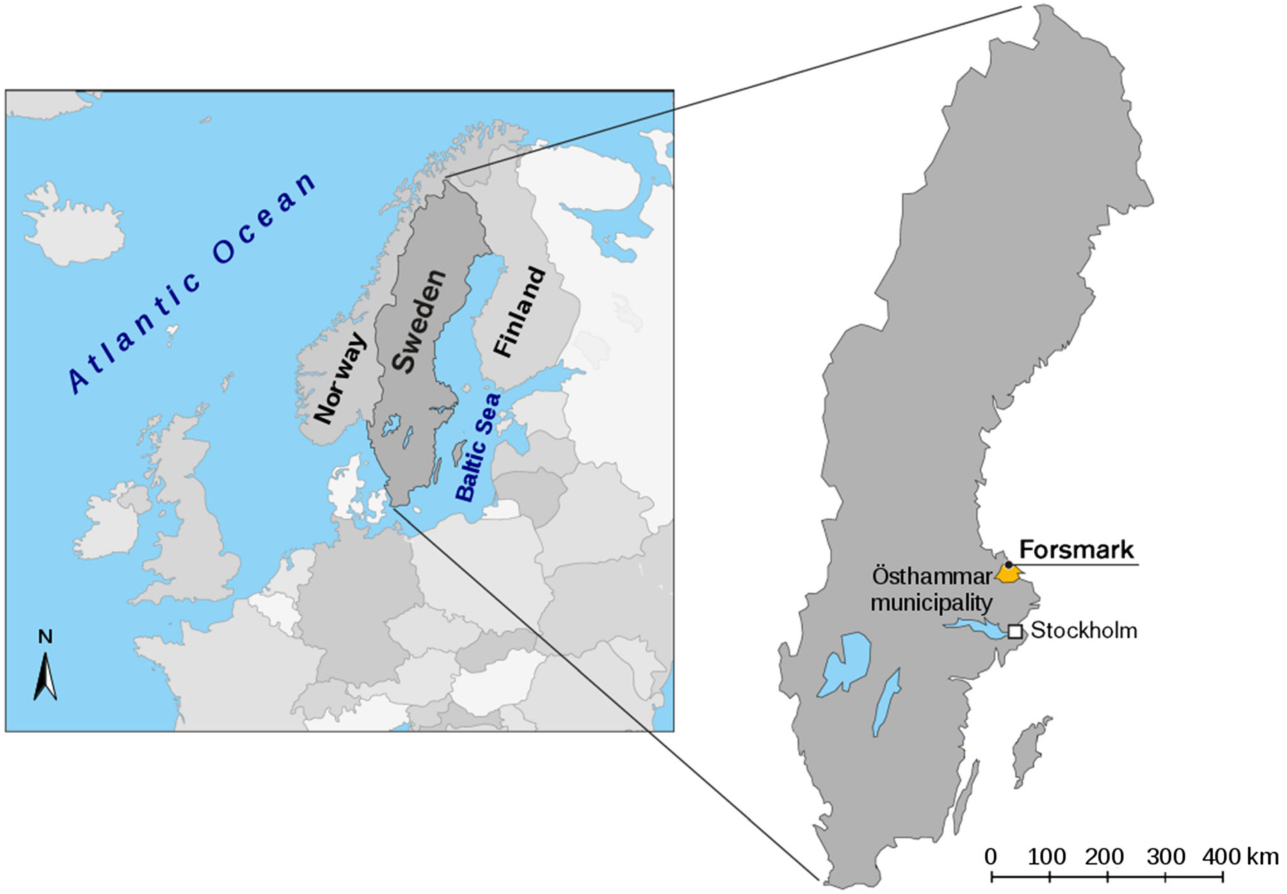

Fig. 2 Location of the Forsmark SNF and LILW repository sites in Sweden

The license application for construction of the SNF repository has been reviewed by the Swedish Radiation Safety Authority (SSM) and is currently under consideration by the Swedish government. An application to expand the existing LILW repository (SKB 2015) is also under review by SSM.

The bedrock at Forsmark is part of the Fennoscandian Shield, and consists mainly of Proterozoic granite or granodiorite that formed around 1.85 Ga and was subsequently subjected to varying degrees of low-grade metamorphism and ductile deformation while still at mid-crustal depths, then exposed by erosion during the late Proterozoic to form a morphological surface known as the sub-Cambrian peneplain. Subsequent burial by sedimentary rock was followed by a second episode of denudation following the Cretaceous (SKB 2008). The modern bedrock surface closely corresponds to the Cambrian peneplain, with minor displacements of blocks along brittle deformation zones that typically formed by reactivation of earlier ductile fault zones.

In most areas, the bedrock surface is covered by Quaternary deposits less than 5 m deep, consisting of glacial till and glacial or post-glacial clays, silts sands, tills, peat, or gyttja (a lacustrine mud with high organic content formed by decomposition of peat). Topographic relief is low (less than 50 m over the 5 km width of the site). The entire region is subject to post-glacial uplift at a rate of 6 mm/y which, combined with the low relief, implies that the Baltic coastline is retreating at a mean rate of about 0.50 m/y.

Infiltration of meteoric waters to the bedrock is limited by the generally low vertical permeability of the bedrock. Most annual precipitation is believed to flow to the sea either via surficial streams and ditches or via the Quaternary sediments (Jarsjö et al. 2007). The water table generally remains at or just above the bedrock surface year round. Locally, the uppermost 50–100 m of bedrock is characterized by very high horizontal conductivity, due to laterally extensive, nominally horizontal fractures that have large apertures due to stress release and, in some cases, propping by sand dikes interpreted as having been injected by subglacial meltwaters. These features are expected to reduce the effective hydraulic gradients acting at the 450 m depth of the proposed SNF repository, given that the transmissivity of the rock is very low below 150 m depth and the topographic gradients thus are short-circuited.

The geometries and hydrologic properties of the major deformation zones and intervening, sparsely fractured bedrock at the SNF site have been investigated under an extensive surface-based site characterization program which included

25 core-drilled holes 200–1,000 m deep that were characterized with a variety of geophysical logging tools as well as a borehole televiewer for identifying individual fractures, packer testing on 5-m intervals, and a differential flow logging tool, the Posiva Flow Log (PFL; Ludvigson et al. 2002), which also allows identification of individual flowing fractures.

Repository concepts and key hydrogeological performance measures

The proposed SNF repository (SKB 2011) is based on the KBS-3 concept in which the spent nuclear fuel assemblies are encased in a copper-steel canister, which is then placed in deposition holes in excavated tunnels. Each of the deposition holes is about 2 m diameter, 8 m deep and surrounded with compacted bentonite, a clay that swells. Tunnels within the repository are also backfilled with bentonite. As the repository resaturates with water following tunnel closure, the bentonite is expected to swell and minimize both groundwater flow and advective transport adjacent to the canister. The repository is located at a depth where reducing conditions are expected to prevail, so that corrosion of the copper by oxidation is minimal.

Certain parameters have been identified as most significant for the long-term performance (safety) of a SNF repository based on this concept. These parameters are referred to as "performance measures". For a SNF repository, the key hydrogeological performance measures are (1) the groundwater flowrate to or around a given deposition hole (which controls bentonite erosion and canister corrosion under certain circumstances) which in safety analyses by SKB (2010) is expressed as an equivalent flowrate U_{r1} (Neretnieks et al. 2010; Tsang et al. 2015), (2) the advective transport time t_{w} from a deposition hole to the surface, and (3) the transport resistance F_{r} along discharge pathways:

$$F_{\mathrm{r}} = \sum_i \frac{a_{\mathrm{r}i} L_i}{q_i} \tag{1}$$

where $a_{\mathrm{r}i}$ [L^{-1}] is the flow-wetted surface per volume of rock in the ith segment of the discharge path, L_i [L] is the segment length, and q_i [$\mathrm{L\,T}^{-1}$] is the Darcy flux, or equivalently:

$$F_{\mathrm{r}} = \sum_i \frac{a_{\mathrm{w}i} L_i}{u_i} \tag{2}$$

where $a_{\mathrm{w}i}$ [L^{-1}] is the flow-wetted surface per volume of mobile water in the ith segment of the discharge path, and u_i [$\mathrm{L\,T}^{-1}$] is the pore water velocity. The transport resistance F_{r} represents a parameter group that was identified by Robinson and Worgan (1992) and SKI (1997) as governing advective transport of radionuclides subject to matrix diffusion and reversible sorption. It has been used as a key hydrogeological performance measure for models of the proposed SNF repository in Sweden (Joyce et al. 2014). Flow-wetted surface in DFN models for repository applications in crystalline rock is often estimated by simple geometric considerations, as the surface area of both sides of a fracture segment:

$$a_{\mathrm{w}i} = \frac{2}{b_{\mathrm{T}i}} \tag{3}$$

where $b_{\mathrm{T}i}$ is the mean effective aperture for solute transport; this simple approach is also used here.

In contrast to the SNF repository, the LILW facility and its proposed extension consist of 11 waste vaults of different design depending on the type of waste. One of these vaults, called The Silo, is vertically oriented, while the other ten—called 1BMA, 2BMA, 1BLA–5BLA, 1BTF, 2BTF, and BRT—are horizontal caverns with their long axis aligned with the N30E direction.

Most of the vaults are designed to permit flow through relatively permeable backfill or even open volumes that surround waste encased in concrete caissons or metal containers; thus, the vaults are generally highly conductive relative to the surrounding rock. The potential source of radionuclides is both volumetrically larger and much more dispersed in comparison with the highly concentrated sources in a SNF repository. The key parameters affecting safety for this type of repository are the total volumetric flowrates through these vaults, and the fractions of those flowrates that pass through the encasements that surround the waste.

Complex models of the repository sites at Forsmark

The 3D site-descriptive hydrogeological models for the SNF and LILW repositories at Forsmark, as developed for these facilities by the radioactive-waste-management company SKB, are based on a binary division of the bedrock into two main domains: a number of discrete brittle deformation zones with relatively high hydraulic conductivity, embedded in a region of sparsely fractured rock with lower hydraulic conductivity. The threshold values of hydraulic conductivity for distinguishing between these domains have not been strictly defined, but typically, the sparsely fractured domain has hydraulic conductivities less than 10^{-6} m/s at depths less than 150 m, and less than 10^{-8} m/s at greater depths.

Brittle deformation zones with length scales larger than 1 km and with significant hydraulic conductivity are referred to as hydraulic conductor domains (HCDs) and are treated as deterministic features (SKB 2008, 2013). However, deformation zones of smaller scales, less than 1 km in length, might not necessarily have been found and characterized by site investigations, due to limitations on the resolution of topographic lineament analysis and geophysical methods that were used. The likely existence of these smaller-scale, but still hydrogeologically significant, deformation zones was recognized by the site investigators. In the hydrogeological model for the LILW repository site (Öhman et al. 2012), an attempt has been made to identify these zones of brittle deformation from borehole data, but which cannot be linked to lineaments at the surface. They are considered as possible deformation zones (PDZs). These PDZs are assumed to represent a population of similar features that occur at these sites, but have not been fully characterized by the site investigations; in the complex models they are treated as stochastic features.

Two different types of statistical DFN representations of the sparsely fractured bedrock were developed based on these data. The first of these, referred to as the *geological DFN* model, takes into account all natural geological fractures (Fox et al. 2007). The second, referred to as the *hydrogeological DFN* model, includes only the subset of those fractures that are water-conducting (Follin 2008; Selroos and Follin 2014). Hydraulic interference tests were also performed, mainly focused on characterizing the properties and connections among the major deformation zones (Follin 2008; SKB 2008). Further hydrogeological interpretations focused on the LILW repository site were developed by Öhman et al. (2013) and integrated with results from other geoscientific disciplines by SKB (2013).

Numerical implementations of the site-descriptive models were developed using three-dimensional (3D) modeling approaches based on upscaling of stochastic realizations of the DFN models for the sparsely fractured bedrock, in combination with the deterministic HCDs (Hartley et al. 2006; Joyce et al. 2014; Öhman et al. 2013). Due to the long timescales of concern for repository safety, these models also took into account the temporal evolution of the groundwater flow fields resulting from changing climate conditions accompanied by temporal changes in the Baltic shoreline. Thereby, the evolution of groundwater salinities due to infiltration of waters with different salinities during different stages of shoreline migration and climate conditions were accounted for. For both the SNF and LILW repositories, the computer run times for these complex models precluded evaluation of several alternative parameterisations of the DFN models that were developed as part of the site characterization programme. Treatment of possible variants with respect to uncertain hydraulic properties of the HCDs and regolith was likewise limited. Despite the high level of sophistication of these complex models, from a regulatory standpoint the incomplete evaluation of identified uncertainties left open questions as to whether all significant uncertainties in the models had been adequately addressed.

Approach

An SRM as developed in this paper considers a basic recharge-repository-discharge path for groundwater flow, with a series of flow segments described by models that represent the key characteristics of the segment along the flow path. These key characteristics are identified based on available information regarding the hydrogeological features of the site, including site-descriptive models and calibrated 3D complex models based on the site-descriptive models. The flow along this path is driven by the difference in hydraulic head between the recharge location and the discharge location.

A SRM consisting of a number of flow segments is depicted in Fig. 3. They are defined as

I. Regolith in the recharge area
II. HCD connected to recharge area
III. Sparsely fractured rock mass between (II) and the repository facility
IV. Repository facility
V. Sparsely fractured bedrock between the repository facility and (VI)
VI. HCD connected to discharge area
VII. Regolith in the discharge area

For each segment of this model, a SRM component is identified based on information from the detailed site descriptive models, combined with hydrogeological reasoning. The specific form of these SRM components depends on both the hydrogeological characteristics of the site and the long-term performance measures that have been identified as most important for safety, see section 'Repository concepts and key hydrogeological performance measures'.

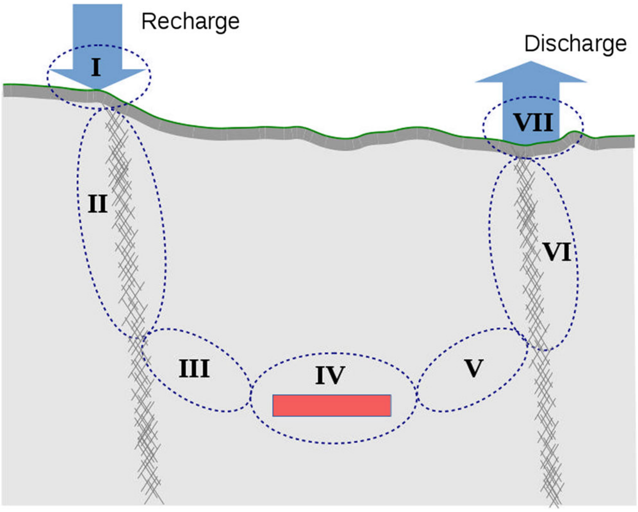

Fig. 3 Simplified representative model of a recharge-discharge system for a waste storage facility in fractured crystalline bedrock with a recharge path consisting of (I) regolith in the recharge area, (II) fracture zone with relatively high transmissivity, and (III) sparsely fractured rock mass between (II) and the facility (IV), and a discharge path consisting of (V) sparsely fractured bedrock, (VI) a second fracture zone, and (VII) regolith in the discharge area

For the present work, each segment is represented in the simplest way by a 1D flow path under a hydraulic gradient, with the possibility of more than one variant of the 1D flow. Each variant represents a formulation that is consistent with available site data and information, and yet is different from alternative formulations.

For the sake of simplicity, the SRMs presented here focus on the temperate-climate period and do not explicitly account for details of physics associated with freshwater/saline-water interfaces in the Baltic coastal setting. For a comprehensive safety assessment, longer time periods with changing surface climate conditions, including glaciation, may need to be taken into account, possibly requiring representation of other aspects in an SRM. The effects of variable density due to groundwaters of different salinity linked to its origin either from precipitation, the Baltic Sea with its brackish water, or from the deep rock with high salinity are not explicitly accounted for.

For each segment, the relationship between volumetric flowrate and potential head difference is considered to be linear:

$$Q = -C\Delta h \tag{4}$$

where Q is the volumetric flowrate [L^3/T] and Δh is head difference between outlet and inlet ends of the segment [L]. The constant C, referred to here as the hydraulic conductance, has units of [L^2/T].

For the case where a given segment is treated as a porous medium with hydraulic conductivity K in the direction of flow, C is given by:

$$C = KA/L \tag{5}$$

where A is the cross-sectional area through which flow takes place, and L is the distance, giving:

$$Q = -KA\Delta h/L \tag{6}$$

which can be recognized as the elementary form of Darcy's law.

When flow through a given segment is considered to take place via a tabular feature—such as a deformation zone, single fracture, or tabular aquifer—with a specified transmissivity T, the hydraulic conductance is:

$$C = Tw/L \tag{7}$$

where w is the nominal width of the tabular feature that participates in flow, giving:

$$Q = -Tw\Delta h/L \tag{8}$$

which is the conventional formula for 1D flow through an aquifer of width w.

Flow through the series of segments that make up the SRM can be calculated as:

$$Q = C_{\mathrm{system}}(h_{\mathrm{in}} - h_{\mathrm{out}}) \tag{9}$$

where C_{system} is the effective conductance of the series of segments C_i:

$$C_{\mathrm{system}} = \frac{1}{\sum_i \frac{1}{C_i}} \tag{10}$$

The preceding represents the basic formulation for the SRM flow segments which will be used to defined flow segments I–VII as discussed in the following. The SRM approach allows for consideration of alternative representations, or variants, of each of the segments in the recharge-discharge path and these are discussed in sequence in the following.

Regolith in the recharge and discharge areas: flow segments I and VII

The regolith in the recharge area (flow segment I) could conceivably limit groundwater flux to an HCD in the next flow segment. In such a situation, the vertical component of groundwater flow through the regolith is of chief concern; therefore, the SRM for the regolith in the recharge area is based on its local vertical hydraulic conductivity, and its local thickness. These parameters have been characterized by detailed mapping of soil types in the terrestrial areas of the site.

For the base case of the SRM for the LILW repository, the regolith in the recharge area is assumed to be coarse till, as this is the most widespread flow-limiting layer across modern terrestrial areas of the site (Bosson et al. 2010; Odén et al. 2014). Sensitivity calculations considered alternative types of regolith based on the values of vertical hydraulic conductivity given by Bosson et al. (2010).

The regolith in the discharge area (flow segment VII) could conceivably limit groundwater flux from a highly permeable fracture zone. As for the recharge part of the path, in such a situation, the vertical component of groundwater flow through the regolith is of chief concern. For the base case of the SRM for the LILW repository, the regolith in the discharge area is assumed to be clay as this is the lowest-conductivity seabed layer in the characterization by Bosson et al. (2010), whereas the nominal thickness is assumed to be 1 m. The importance of seabed sediments was tested by a variant in which the hydraulic conductivity of this layer was assigned the same hydraulic conductivity as the shallow fractured bedrock, with $K_v = 1.5 \times 10^{-6}$ m/s.

For the SNF repository, the capacity of the regolith in the recharge area (flow segment I) to constrain flow is neglected on grounds of conservatism and the likelihood of future changes. Similarly, the role of the regolith in resisting discharge (flow segment VII) has also been neglected on grounds of conservatism. Safety analysis for this type of repository requires consideration of very long time scales, thousands of years into the future when surficial sediments may have been removed or rearranged by glaciation or other processes. Therefore, the most conservative assumption for calculation of radionuclide transport for SNF repository is to assume that the regolith is absent, both in the recharge and discharge areas.

Deformation zones in recharge and discharge portions of the flow path: flow segments II and VI

Hydraulic conductor domains (HCDs) at the Forsmark site are understood to have a sufficiently high density of fractures such that each fracture has numerous connections to other fractures, so that the hydrogeological behavior of the HCD is analogous to a continuously permeable aquifer rather than a discontinuous, discrete fracture network. Thus, these are adequately characterized by a transmissivity value (which may be spatially variable) rather than by a statistical DFN model.

The SRM component for recharging HCDs is based on the evaluated transmissivity of the zones that have been investigated. For the LILW repository, the base-case value of transmissivity is based on a relatively transmissive HCD that is close to the repository, resulting in a relatively short path through the sparsely fractured bedrock. The SRM component for discharging HCDs is based on the evaluated transmissivity of the HCDs that have been investigated and which presently outcrop below the sea, where future discharge is expected following shoreline retreat, based on large-scale hydrogeological modelling.

Transmissivities of some HCDs for the LILW facility were uncertain due to changes in site-characterization equipment and methods over time. According to Öhman et al. (2012), the HCD intercepts assessed based on older data tended to have higher interpreted transmissivities than those based on newer data, by roughly an order of magnitude. The sensitivity of results to this uncertainty is evaluated by considering an order-of-magnitude increase in HCD transmissivities in the SRM, for both the recharge and discharge paths.

For the analysis of the SNF repository, the role of HCDs in resisting recharge and discharge has been neglected on grounds of conservatism; thus, hydraulic head differences due to surface topography are assumed to propagate to the depth of the repository, with negligible restriction by the deformation zones. Previous calculations using complex DFN models for a hypothetical SNF repository at sites with similar bedrock characteristics (Geier 1996; Joyce et al. 2014) showed that HCDs accounted for only a very small fraction of the total transport resistance for radionuclides traveling from a leaking spent-fuel canister to the surface environment.

Rock mass between the recharging deformation zone and the repository: flow segments III and V

The rock mass connecting deformation zones to the repository, whether on the recharge or discharge part, is the most irregular part of the system. For both the SNF repository and the LILW facility, the rock mass has been characterized in terms of a DFN statistical model within the framework of a complex model by SKB, with probability distributions for different fracture properties as summarized in the electronic supplementary material (ESM).

For the SRM analysis of the SNF repository, from previous DFN modelling it was expected that this portion of the rock would provide the main transport resistance and thus have the most significant impact on safety. The key issue related to long-term prediction of flow and transport in this flow segment is whether and which fractures happened to connect and provide a path with the lowest transport resistance between a leaking spent-fuel canister and a discharging fracture zone. Therefore, the SRM for this component will be based on a simplified stochastic DFN representation that takes into account the probability distribution for fracture size and alternative statistical models for the correlation of fracture hydraulic properties to size. This SRM for the rock mass is described in further detail in the following.

For the LILW facility, due to the larger and more dispersed source of radionuclides, long-term safety is expected to depend more on overall flows through the waste vaults than on localized flow paths; hence, the SRM for the LILW facility focuses on pathways that have a potential to produce high flows through a given vault. Two alternative simplified representations were considered to represent (1) direct connection via a minor deformation zone of a scale that might reasonably have been missed by the site characterization programme, and (2) bulk flow through the rock mass as represented by an ECPM model.

The potential effect of PDZs was scoped by considering the case where flow through the sparsely fractured rock, both along the recharge and discharge paths, occurs through single features with transmissivities representative of PDZs. The transmissivity values for the PDZs were drawn from the values tabulated by Öhman et al. (2012). Two approaches were considered: (1) random sampling from this table of values and (2) selection of the maximum value. The latter approach is more conservative and was therefore used to scope the maximum plausible effect of unresolved PDZs providing high-transmissivity paths through the bedrock.

SRM for connective paths through the rock mass for the SNF repository

Starting with the DFN models which have been developed to represent the fractured rock mass in this flow segment, the

SRM for this case is based on repository layouts that are adapted to specific stochastic realizations of the DFN model. In these layouts, the locations of SNF deposition holes are selected based on criteria to avoid large fractures that can be identified from tunnel walls (Munier 2010; Hedin 2010). Then the starting points for potential radionuclide flow paths in the SRM are deposition holes that are intersected by fractures, despite these criteria. They are chosen at random by Monte Carlo sampling from the set of intersections between the deposition holes and fractures from the DFN model. Ten DFN realizations were considered, each with a different configuration of adapted deposition holes giving rise to a separate set of 1D flow and transport paths.

The linear frequency (per length of deposition hole) $P_{10,\mathrm{trans}}$ of transport paths connecting from deposition holes through the DFN to an ensemble of discharging HCDs is defined as:

$$P_{10,\mathrm{trans}} = \frac{N_{\mathrm{trans}}}{L_{\mathrm{dh}} N_{\mathrm{dh}}} \tag{11}$$

where N_{trans} is the expected number of transport paths in the repository section, L_{dh} is the deposition hole length (7.83 m), and N_{dh} is the number of deposition holes in the repository section.

$P_{10,\mathrm{trans}}$ is assumed to be equal to $P_{10,\mathrm{PFL,corr}}$, the total linear frequency of flowing features identified by the Posiva flow log measuring device (PFL) from deep core-drilled holes. The values used for the rock below $z = -400$ m are $P_{10,\mathrm{PFL,corr}} = 0.005\ \mathrm{m}^{-1}$ for the main host rock unit for the repository and $P_{10,\mathrm{PFL,corr}} = 0.05\ \mathrm{m}^{-1}$ for a secondary host rock unit found in the proposed repository.

The geometric DFN simulations only consider fractures with radius larger than 3.5 m. These calculations do not take into account deposition holes that could be connected along tunnels via an excavation-damaged zone (Tsang et al. 2005), or are connected only via very low-T fractures that would be below the PFL detection limit. Such deposition holes would be unlikely to experience significant buffer erosion or canister corrosion (according to SKB's models of those processes).

In the SRM, a given fracture-deposition hole intersection is assumed to have a uniform probability p_c of connecting to the nearest discharging HCD. Two different assumptions are considered regarding this probability, length-based scaling and area-based scaling, as detailed in the ESM.

Each transport path is assumed to consist of a minimum number of links in a sequence that are necessary to connect to the nearest point on the closest discharging HCD (Fig. 4), subject to two constraints:

1. The first link in the flow path is the fracture that intersects the deposition hole, with length equal to the fracture radius (known from the DFN realization)

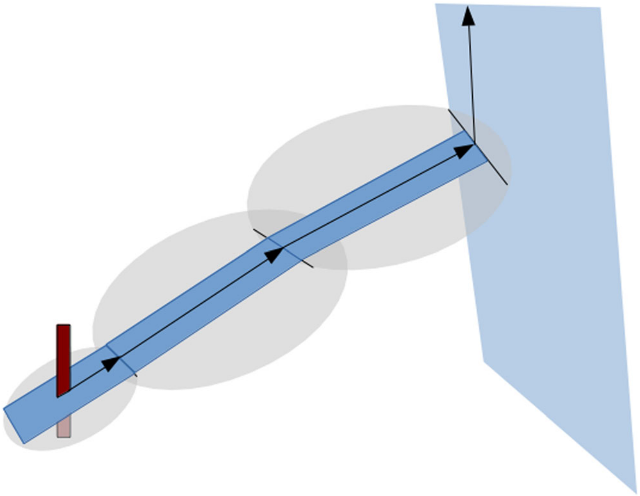

Fig. 4 Conceptual illustration of transport path links as channels of constant width in a series of three fractures connecting from a deposition hole to the nearest hydraulically conductive deformation zone. The arrows indicate the direction of transport

2. The second link (and third, fourth, etc. links if needed) are assumed to be of length equal to the remaining distance to the HCD, or the maximum fracture radius $r_{\max} = (1{,}000\ \mathrm{m})/\sqrt{\pi}$, whichever is less.

The main assumptions introduced by these constraints are:

1. The radius of the fracture that intersects the deposition hole provides a reasonable estimate of the length of the connection from the deposition hole to the nearest fracture that connects to the larger-scale hydraulic network.
2. Stochastic fractures (or minor deformation zones) are not larger than the 1,000-m scale as estimated by SKB (2008).
3. The transport path is directly joined to the nearest point on the nearest discharging HCD, with negligible tortuosity (i.e., sinuosity of flow channels within the fracture plane) so that the actual distance traveled by water moving through the fracture is not significantly greater than the Euclidean distance between inlet and outlet points.

The first assumption is reasonably conservative, because in most cases this first link is the shortest link in the pathway, and hence, for the typical case where fracture transmissivity is positively correlated to fracture size, this will be the lowest-transmissivity link, which accounts for the major part of the transport time through the rock t_{w} and the corresponding transport resistance F_{r}.

A more strictly conservative assumption would be to assume that the length of the first link is negligible so that this first fracture does not contribute significantly to either t_{w} or F_{r}. However, such a conservative assumption is not realistic as the criteria for adaptive placement of deposition holes imply that the first link in a transport path will be via a relatively small-radius fracture in most cases.

An intermediate assumption (more conservative than the first assumption, but more realistic than neglecting the first link) would be to assume that the first link extends for just a short distance, less than the fracture radius, before connecting to the large-scale fracture network. However, such an assumption may still be excessively conservative in view of the long mixing lengths inferred from experiments in similar geological media (Black et al. 2017; Figueiredo et al. 2016).

The second assumption—that stochastic fractures forming the second and subsequent links of a transport path are not larger than 1,000 m in extent—hinges upon whether the site investigations have really managed to exclude larger fractures or minor deformation zones.

An alternative and more conservative assumption would be that the second link of a transport path always connects directly to the nearest discharging HCD, which would be inconsistent with the site descriptive model, but arguably has not been excluded by the site investigations. This third assumption of a direct path is purely conservative. Any alternative assumption of greater tortuosity would require a longer transport-path length L_r and would give rise to higher values of t_w and F_r. Perhaps some higher degree of tortuosity would be more realistic and alternative assumptions for tortuosity could be considered within this approach, but it is expected that the effects on transport-path parameters would be less than an order of magnitude.

Transmissivity values for each link are assigned as deterministic or stochastic functions of the link length, using one of three different relationships that were proposed in the site descriptive model (SKB 2008). Transport apertures in turn are assigned as deterministic or stochastic functions of transmissivity. These relationships among length, transmissivity, and transport aperture are detailed in the ESM. Using these values together with the estimated hydraulic head differential along the discharge path, the parameters relevant for safety (flowrate and transport resistance) can be calculated.

SRM for rock mass treated as ECPM for the LILW repository

The rock mass around the LILW repository is represented by an ECPM whose effective hydraulic conductivity value can be derived by stochastic simulations of DFN statistical models (SKB 2013). An ECPM representation is reasonable because release of radiation from the LILW repository is expected to depend mainly on bulk flows through the vaults, rather than discrete flows to individual waste containers as in the SNF repository. Two alternative analyses to evaluate the effective conductivity value were used and they are referred to as the connectivity-analysis and tectonic-continuum alternatives (see ESM). For each of these alternatives, directional hydraulic conductivities in each of the three directions *x* (east–west), *y* (north–south), and *z* (vertical) on the 50-m blocks are sampled from larger-scale realizations, using the geometrical formulas of Oda (1985). These directional hydraulic conductivity values K_x, K_y, and K_z are used for the ECPM representation.

The base case of the SRM uses the geometrical mean values of K_x, K_y, and K_z to represent the rock mass in all flow segments of the model. This includes rock mass segments of the recharge and discharge paths (flow segments III and V), as well as the rock mass associated with each vault (flow segment IV) as discussed in the following section 'Repository components: flow segment IV'.

For the calculation cases referred to as "permeameter" cases, a $\{K_x, K_y, K_z\}$ triplet for each rock mass segment in the simplified model is sampled randomly from the set of 1,200 blocks within the repository depth range for which $\{K_x, K_y, K_z\}$ estimates were calculated by Geier (2017). Thus in these calculation cases, the rock mass segments of the recharge and discharge paths have independent K values. The effective hydraulic conductivity for a given orientation is calculated from these triplets based on the assumption of a permeability ellipsoid with principal components aligned with the *x*-, *y*-, and *z*-directions. In practice, the block-scale hydraulic conductivities derived from the DFN model tend to be close to isotropic in the horizontal plane, with anisotropy ratios mainly in the range 0.9–1.1, so the effect of this calculation on the SRM is minor.

SRM for rock mass via possible deformation zones for the LILW repository

The existence of possible deformation zones (PDZs) with length of less than 1 km has been recognized based on indications from borehole data (see section 'Complex models of the repository sites at Forsmark'). Their detailed geometric information is however not available. The potential effect of PDZs was scoped by considering the case where flow through the sparsely fractured rock, both along the recharge and discharge paths, occurs through single features with transmissivities representative of PDZs. The size of the PDZs, represented as squares in the complex model, is considered to be represented by a uniform distribution of side lengths from 1 to 1,000 m. In the SRM, only PDZs longer than L_{rm} need be considered as the class of PDZs that can form direct connections over this distance. The transmissivity of each PDZ is treated as homogeneous and is sampled from transmissivities evaluated from borehole intercepts, as tabulated by Öhman et al. (2012). Two approaches were considered: (1) random sampling from this table of values and (2) selection of the maximum value. The latter approach is more conservative and was therefore used to scope the maximum plausible effect of unresolved PDZs providing high-transmissivity paths through the bedrock.

Repository components: flow segment IV

For the SRM of the SNF repository, the only repository components considered are the deposition holes in which the spent-fuel containers are to be emplaced. The repository design calls for the annulus of these holes outside the containers to be backfilled with compacted bentonite, which is expected to swell as the repository resaturates with water, forming a barrier to advection; however, under certain groundwater chemistry conditions, the bentonite might be substantially eroded. In the SRM, any resistance to flow by the backfill material in the deposition hole is neglected.

Waste-storage vaults in the LILW repository are represented as simple 1D conductors. For the sake of simplicity, the description here pertains to the SRM representation of one type of vault, the concrete tank vaults that are named, 1BTF and 2BTF. The SRM representations of the other vaults in the LILW facility are conceptually similar but differ in the details as documented by Geier (2017).

The dimensions of 1BTF and 2BTF vaults are identical, as specified by SKB (2014). The simplified component model for longitudinal flow along each of these vaults is depicted in Fig. 5. For the section of the vault that contains the waste, there are two conductors in parallel, representing the encased waste and the backfill above the waste.

The net effect of the two backfilled sections at either end of the waste vault for flow is accounted for by a conductive segment placed in series with the waste-storage section. The conductance of this segment is calculated as:

$$C = \frac{K_{\mathrm{backfill}} A_{\mathrm{vault}}}{L_{\mathrm{vault}} - L_{\mathrm{waste}}} \tag{12}$$

where A_{vault} is the cross-sectional area of the vault. The potential for bypass flow through the rock mass surrounding the vault is accounted for by a parallel conductance equal to:

$$C = \frac{K_{\mathrm{rock}} A_{\mathrm{rock}}}{L_{\mathrm{vault}}} \tag{13}$$

where A_{rock} is the cross-sectional area of an annulus of thickness d_{rock} of rock around the vault.

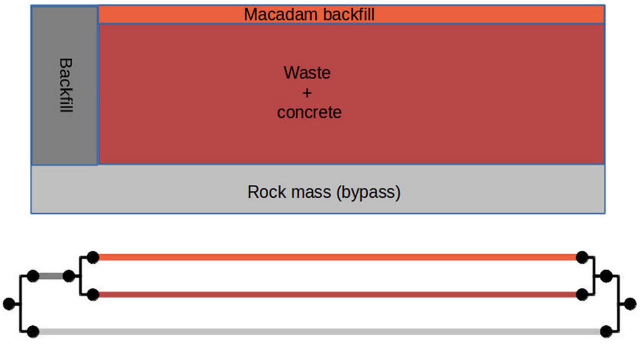

Fig. 5 Simplified component model for 1BTF and 2BTF

Results and discussion

Comparison of SRM with complex model of the SNF repository

The base case of the SRM for the SNF repository is formed by defining the base-case representations of each of the flow segments (see section 'Approach'). Distributions of the performance measures that control long-term safety (equivalent flowrate U_{r1}, transport resistance F_{r}, and advective transport time t_{w}, see section 'Repository concepts and key hydrogeological performance measures') are obtained as a consequence of the variable properties and geometric locations of fractures that intersect deposition holes in the DFN simulations of the repository layout (see section 'SRM for connective paths through the rock mass for the SNF repository').

The results of the base case are generally similar to results from the complex model of SKB (2011) as presented in Table 1 and in Figs. 6 and 7. The SRM yields slightly higher values of U_{r1} (which is more conservative for safety, as higher flows lead to higher risk of radionuclides leaking from the repository), but within a factor of 2. The values of F_{r} from the SRM are generally lower than those from the complex model (which again is more conservative for safety, as lower values imply less effective retardation of radionuclide transport), but within an order of magnitude for the most extreme low values, and practically converging to the same results for the upper part of the F_{r} distribution. Thus, the SRM gives values of the key performance measures that are close to or slightly more conservative than those from the complex model, and confirms the conclusions regarding the hydrogeological influences on the long-term safety of the facility.

The variability between realizations of the SRM, for both U_{r1} and F_{r}, is notably very small. This is apparently a result of the strong constraint provided by the criteria for avoiding large-radius fractures (Munier 2010; Hedin 2010); in combination with the correlations between fracture radius and fracture hydraulic properties of transmissivity and transport aperture, as incorporated in the base case of the SRM.

Comparison of SRM with complex model of the LILW repository

The base case of the SRM for the LILW repository is formed by defining the base-case representations of each of the flow segments as described in section 'Approach'. Figure 8 compares results for the base case with results of the complex model (SKB 2015). Results are shown for two versions of the base case, representing two contrasting assumptions of how flow is partitioned among the vaults:

Table 1 Comparison of the base cases of the SRM and the complex model for the SNF repository in terms of statistics for the performance measures U_{r1} and F_r

Statistic	Complex model U_{r1} (m/y)	SRM U_{r1} (m/y)	Complex model F_r (y/m)	SRM F_r (y/m)
Minimum	–	–	4×10^3	4×10^2–8×10^3
10th percentile	1.6×10^{-6}	1.8×10^{-6}	5×10^5	1×10^5
Median	1.0×10^{-5}	2×10^{-5}	2.5×10^6	2.5×10^6
90th percentile	1.6×10^{-4}	2.5×10^{-4}	4×10^7	3×10^7
Maximum	1×10^{-2}	1×10^{-2}	–	–

Values for the complex model are estimated graphically from Figure 6-28 of Joyce et al. (2010). The base-case variants of both models assume a semicorrelated relationship between transmissivity and fracture size, in combination with the base-case (Äspö Task Force) model for aperture

1. Each vault responds individually, as part of a distinct recharge-discharge path.
2. Vaults in each section of the repository (the existing facility and its proposed extension) respond as conductors in parallel.

The first assumption is more conservative, as it leads to the highest flows through each vault. The second assumption is considered more realistic, as it accounts for the likelihood that flow will be divided among the vaults in proportion to their conductances.

For most vaults, the SRM results for these two different assumptions bracket the flowrates calculated by the complex model for times approximately 1,000 years after present (AD 3000), at which point the Baltic has retreated sufficiently for the assumed value of Δh to be realistic. The exceptions are vaults 1-2BMA and 1BLA, where flows calculated with the complex model exceed the SRM results by less than a factor of 2. The SRM results for the silo differ from the results of the complex model by much larger factors, but still bracket those result; thus, the SRM gives confidence that the flowrates calculated using the complex model are within reasonable bounds.

Evaluation of key uncertainties for SNF repository using SRM variants

The SRM approach, being simple, provides a transparent framework to check sensitivity of long-term safety to hydrogeological concepts, parametric uncertainties, and alternative constitutive relationships. These sensitivities are studied in terms of SRM variants, each of which is formulated to evaluate the impact of a particular source of uncertainty. This and the following section give examples of how the SRM

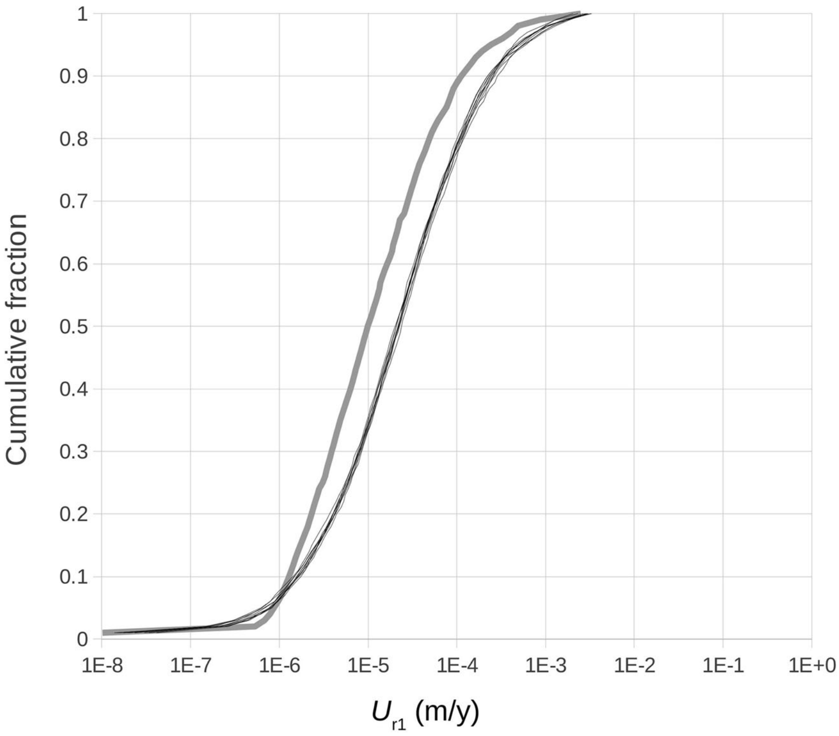

Fig. 6 Comparison of SRM and complex model results for the SNF repository in terms of the cumulative distributions of equivalent flowrate U_{r1}. Thick gray curve shows results of the hydrogeological base case for the complex model for conditions in AD 3000 (Joyce et al. 2010). Thin black curves show results for ten realizations of the base case of the SRM

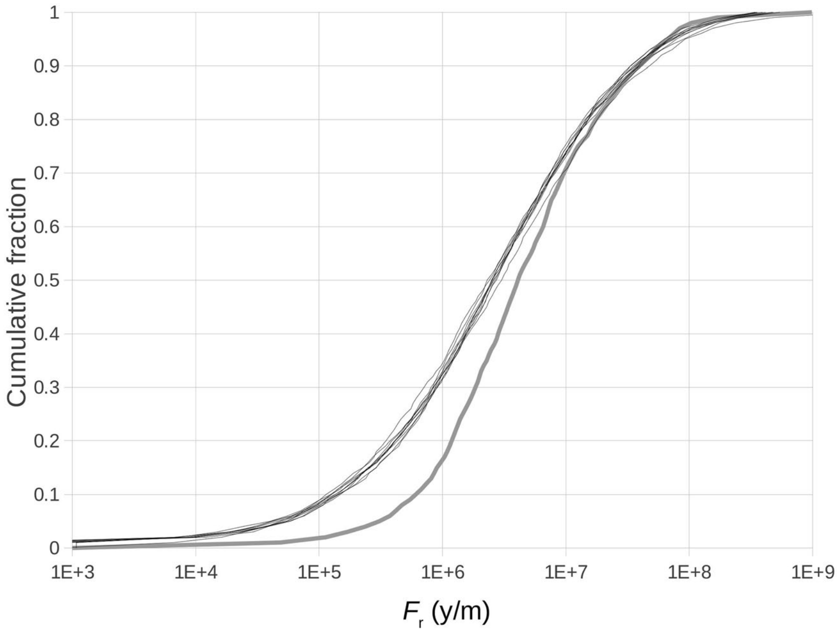

Fig. 7 Comparison of SRM and complex model results for the SNF repository in terms of the cumulative distributions of transport resistance F_r. Thick gray curve shows results of the hydrogeological base case for the complex model for conditions in AD 3000 (Joyce et al. 2010). Thin black curves show results for ten realizations of the base case of the SRM

approach has been used to explore the impact of particular sources of uncertainty for long-term safety of the SNF repository and the LILW repository.

The main uncertainties evaluated for the SNF repository are assumptions regarding the DFN model for the rock mass on the discharge path (flow segment V), including:

1. Three alternative geometrical parameterizations of the DFN (see the ESM)
2. Alternative models for the correlation of transmissivity to fracture size (see the ESM)
3. Alternative models for the correlation of fracture transport aperture to transmissivity (see the ESM)

The main effects of the alternative geometrical parameterizations are in terms of the number of deposition holes that connect to transport pathways. These are directly a result of differences between these alternatives in terms of intersections with deposition holes (Table 2). The two alternatives to the base case both produce more intersections with deposition holes. For area-based scaling (which assumes that the probability of intersecting a given flow channel scales in proportion to the vertical cross-

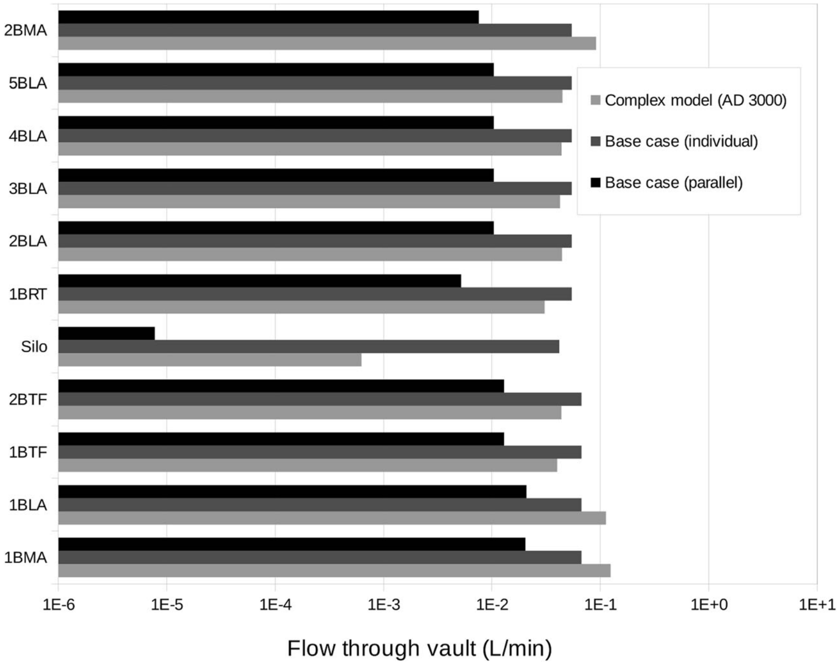

Fig. 8 Comparison of simplified model base-case results in terms of flowrates through waste vaults, versus flowrates calculated using the complex model for the safety assessment (SKB 2015) for AD 3000, shown as gray bars. Dark gray bars show SRM flowrates for the case where each individual vault is considered separately. Black bars show SRM flowrates for the case where each of the vaults within each section of the repository are treated as conductors in parallel

Table 2 Effect of DFN alternatives and frequency scaling method on the predicted numbers N_{trans} of deposition holes that are connected to transport pathways

DFN alternative	Scaling	Min. N_{trans}	Max. N_{trans}	Mean N_{trans}	Median N_{trans}
1	Linear	243	256	246	245
2	Linear	239	245	242	241
3	Linear	224	236	230	231
1	Area	2,057	2,308	2,224	2,245
2	Area	3,921	4,265	4,040	4,031
3	Area	4,924	5,406	5,199	5,192

The total number of deposition holes in the repository is 6,000

sectional area of the deposition holes, see ESM), effectively all intersections count as potential transport paths.

The results for the two main SRM variants that considered alternative size-transmissivity relationships can be compared with those from the complex models (Figs. 9 and 10). For the SRM case in which transmissivity is uncorrelated to size, the predicted values of U_{r1} are again slightly higher (and thus more conservative) than those predicted by the equivalent case of the complex model estimates, but within a factor of 2. The SRM predictions of F_r are also conservative (i.e., generally lower) than those from the complex model, but once again within an order of magnitude for the most extreme low values, and converging to practically the same results for the upper part of the F_r distribution.

When fracture transmissivity is perfectly correlated to size, a contrasting relationship is seen. In terms of U_{r1}, the SRM predicts a much narrower range of values than the corresponding

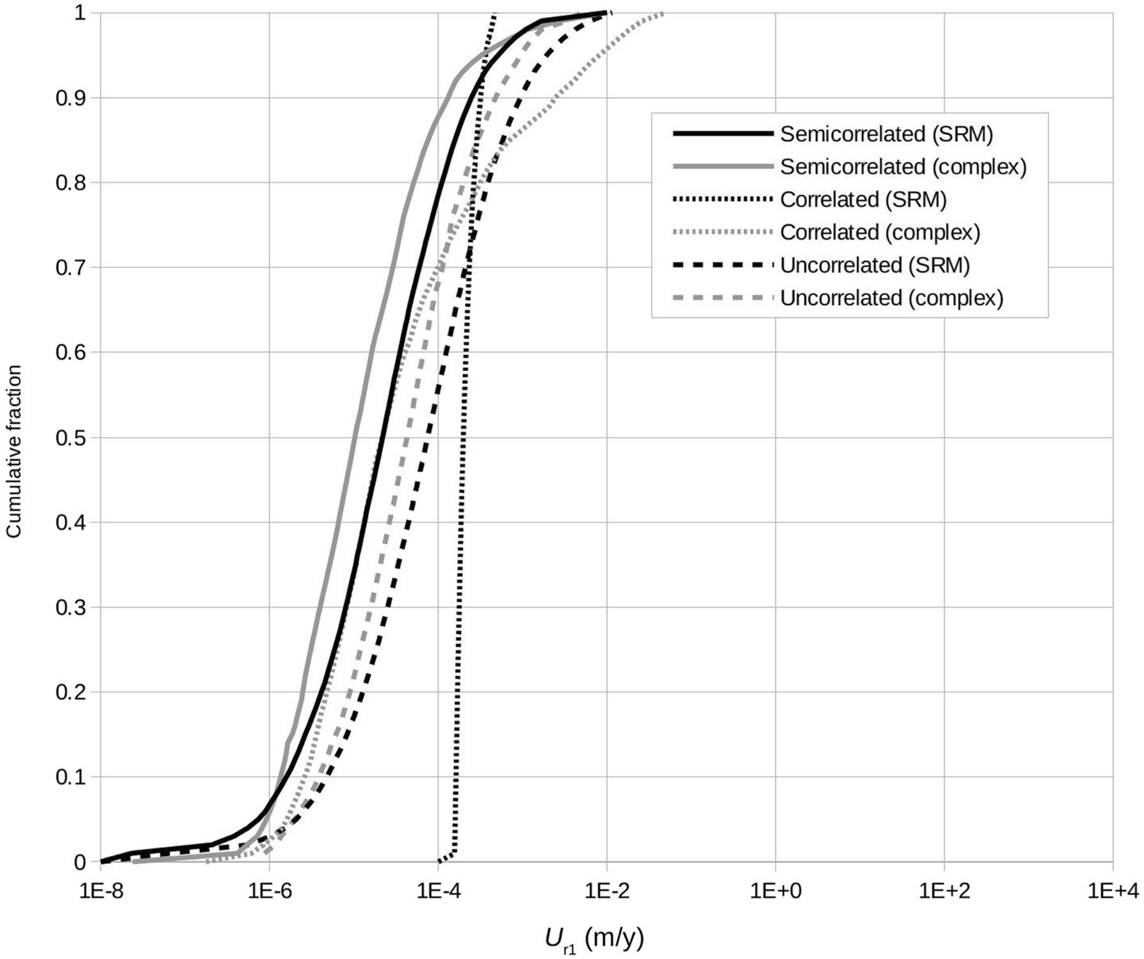

Fig. 9 Comparison of model variants comparing semicorrelated, perfectly correlated and uncorrelated relationships of fracture transmissivity to fracture for the SNF repository in terms of the cumulative distributions of equivalent flowrate U_{r1}. Gray lines show results of these variants of the hydrogeological base case for the complex model (Joyce et al. 2010). Black lines show results of the corresponding variants of the SRM

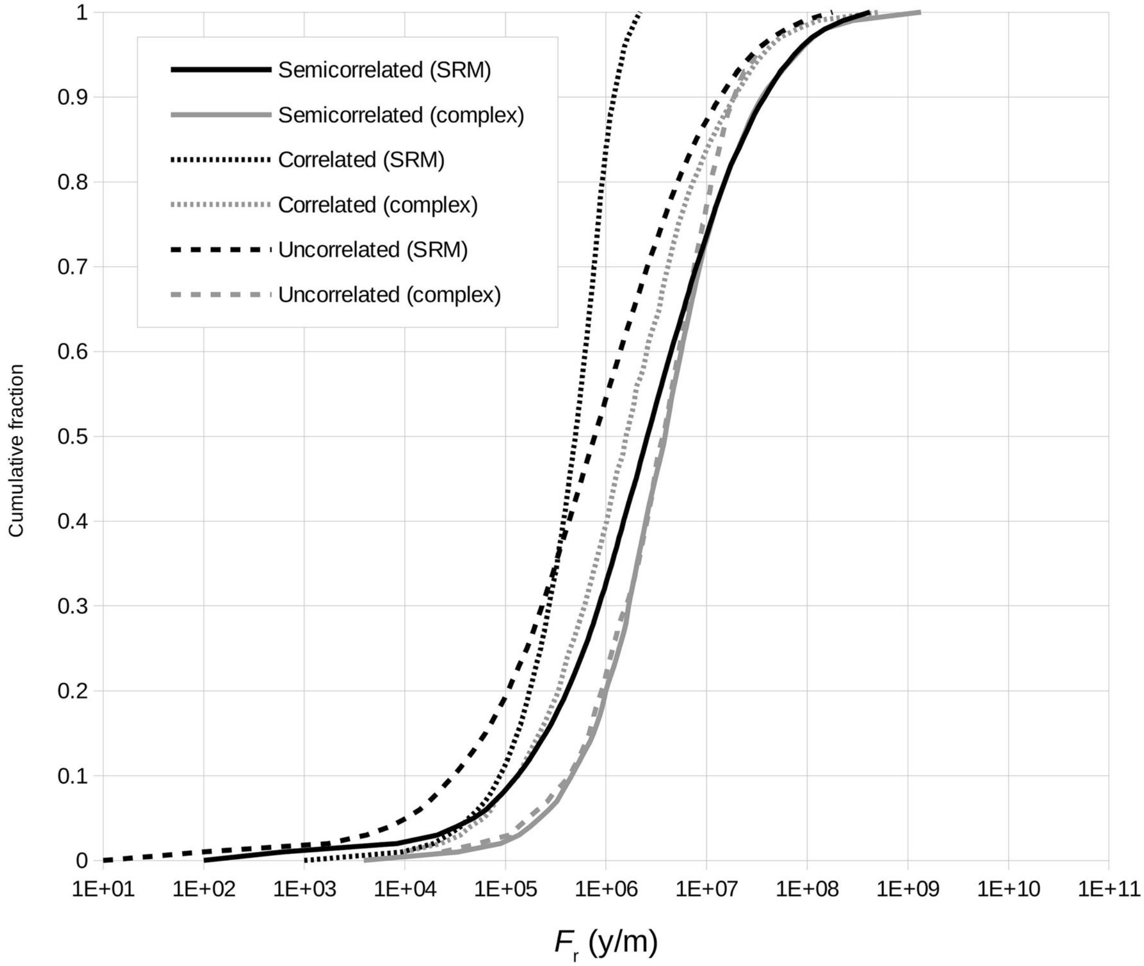

Fig. 10 Comparison of model variants comparing semicorrelated, perfectly correlated and uncorrelated relationships of fracture transmissivity to fracture for the SNF repository in terms of the cumulative distributions of transport resistance F_r. Gray lines show results of these variants of the hydrogeological base case for the complex model (Joyce et al. 2010). Black lines show results of the corresponding variants of the SRM

complex model, and is *less* conservative for the upper part of the distribution. In terms of F_r, the SRM is again less conservative than the complex model by about a factor of about 3 for the most extreme low values, which indicates transport paths that provide near-negligible resistance to release of radionuclides, but slightly more conservative in terms of the 10th percentile values and higher percentiles. These contrasting results for the perfectly correlated case are an artefact of certain simplifying assumptions of the SRM, as discussed in section 'General discussion and concluding remarks'.

The SRM was also used to evaluate combinations of these main variants with different assumptions regarding the relationship between fracture transmissivity T and transport aperture b_T (Fig. 11, for a single realization of each case, using DFN variant 1 with and semicorrelated T vs. r model, with area-based scaling of frequency). The different models for aperture influence the advective transport time t_w, while the difference between the base case and either the stochastic or cubic-law model are minor. An empirical model in which b_T is proportional to $T^{0.3}$ yields significantly longer advective transport times. The alternative models for aperture do not influence either U_{r1} or F_r, due to the way that these are linked to the flux density q under the assumptions used in this model.

Evaluation of key uncertainties for LILW repository using SRM variants

The significance of Baltic seabed sediments (flow segment VII) for resisting discharge is examined with an SRM variant in which this segment has negligible flow resistance. Results show that the differences with the base case are generally less than 0.3%, and thus negligible in comparison with other factors.

Connections through the rock mass via probabilistic deformation zones lead to more significant differences with the base-case results (Table 3; Fig. 12). Direct connections through the rock mass via high-transmissivity PDZs could potentially increase flows to vaults in the existing part of the

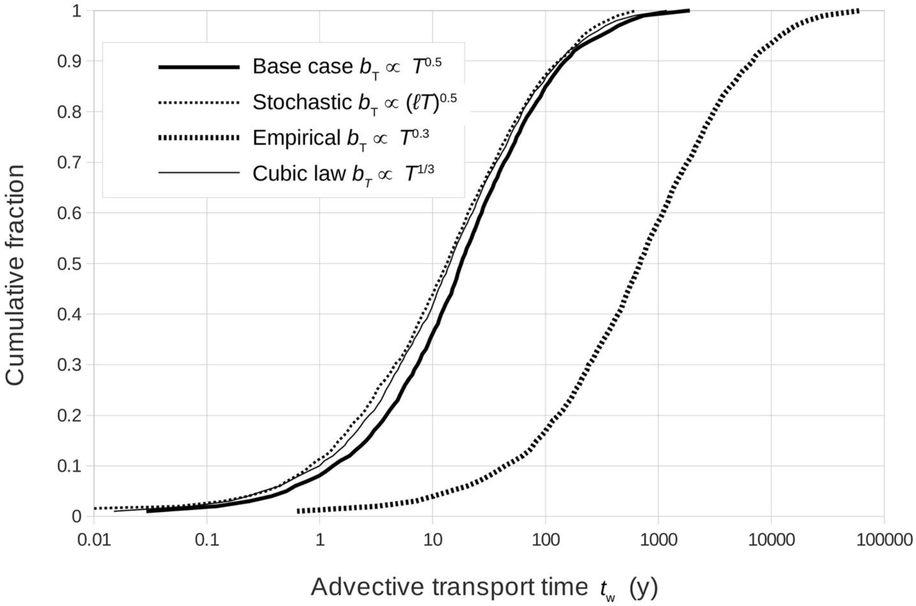

Fig. 11 Effect of alternative relationships of aperture b_T to transmissivity T, in terms of cumulative distributions of performance parameters t_w for a single realization of the SRM, relative to the base case. The symbol ℓ indicates a random lognormal variant. Further details regarding the alternative relationships for aperture are given in the ESM

facility by a factor of 3, and flows to vaults in the proposed new part by a factor of 2.2, relative to the base case.

For the variant in which HCD transmissivities are increased by an order of magnitude to account for uncertainty in their evaluated transmissivities from borehole intercepts, the results (Fig. 12) show an increase in flowrates, relative to the base case, by roughly 40% for the existing vaults and by 70% for the vaults in the proposed new facility. The greater effect for the latter is a consequence of its greater depth, as this implies a longer path through HCDs and thus a proportionally greater distance over which HCD transmissivity limits flow, in this simplified model.

The effect of alternative DFN parameterizations results are shown in Table 4. The differences between the connectivity-analysis model and the tectonic-continuum model are very slight. For both models, the maximum increase in flow relative to the base case is roughly a factor of 3 for the existing vaults, and a factor of 2.2 for the proposed new vaults. Thus the maximum flows resulting from connections via relatively high-conductivity portions of the bedrock, with an ECPM representation based on the DFN models, is similar to the effect of direct connections through the rock mass via PDZs.

The connectivity-analysis model produces a slightly wider range of flowrates for a given vault. This can be explained in terms of the observations (see the ESM) that the connectivity-analysis model has slightly more low-K_g blocks relative to the tectonic-continuum model, but also slightly higher number of high-K_g blocks with $K_g > 2 \times 10^{-7}$ m/s.

General discussion and concluding remarks

Lessons learned from comparison of results from SRMs and complex model

Within the simplification of the SRM for the SNF repository, the performance measures from the SRM are found to be almost entirely determined by the size and transmissivity of the first fracture to intersect a given deposition hole and then

Table 3 Comparison of flowrates (L/min) between the base-case model and the PDZ and high-transmissivity HCD variants, for the two different assumptions regarding flow partitioning among vaults

Vault	Individual base case	Individual PDZ	Individual high-T HCD	Parallel base case	Parallel PDZ	Parallel high-T HCD
1BMA	0.06688	0.20454	0.02867	0.02031	0.06215	0.09438
1BLA	0.06688	0.20454	0.02927	0.02074	0.06344	0.09438
1BTF	0.06687	0.20446	0.01823	0.01292	0.03951	0.09437
2BTF	0.06687	0.20446	0.01823	0.01292	0.03951	0.09437
Silo	0.04172	0.07192	0.00001	0.00001	0.00002	0.05099
1BRT	0.05430	0.11974	0.00875	0.00520	0.01147	0.09136
2BLA	0.05432	0.11980	0.01749	0.01039	0.02292	0.09139
3BLA	0.05432	0.11980	0.01749	0.01039	0.02292	0.09139
4BLA	0.05432	0.11980	0.01749	0.01039	0.02292	0.09139
5BLA	0.05432	0.11980	0.01749	0.01039	0.02292	0.09139
2BMA	0.05431	0.11977	0.01273	0.00757	0.01669	0.09138

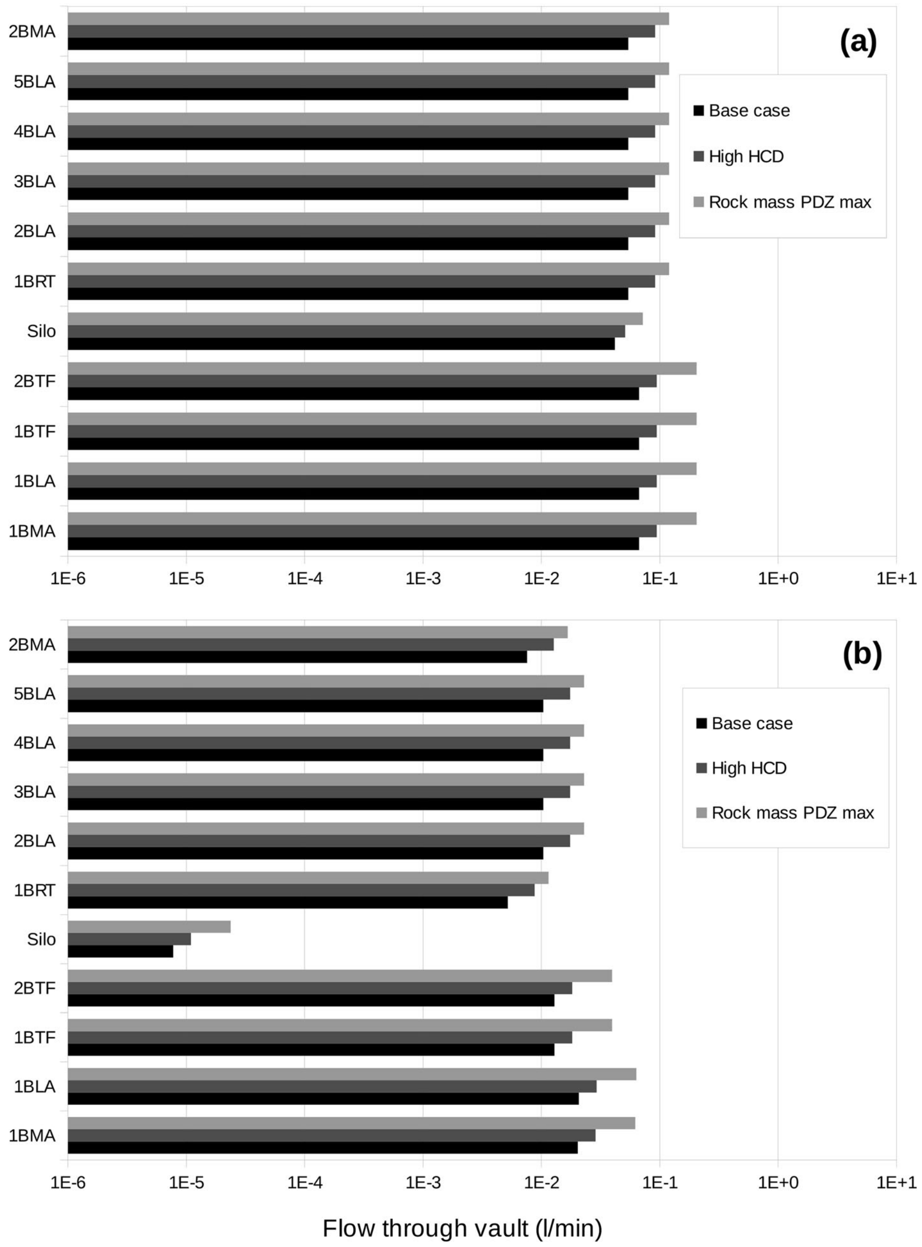

Fig. 12 Comparison of calculation cases representing (dark gray) an order-of-magnitude increase in HCD transmissivities and (light gray) connections to the repository via probabilistic deformation zones (PDZs), relative to the base case of the SRM. **a** Flowrates for the case where each individual vault is considered separately. **b** Flowrates for the case where each of the vaults within each section of the repository are treated as conductors in parallel

Table 4 Comparison of flowrates (L/min) between the base-case model and the two variants based on sampling upscaled hydraulic conductivities from the connectivity-analysis (CA) and tectonic-continuum (TC) variants of the DFN parameterization, for each of the two different assumptions regarding flow partitioning among vaults

Vault	Individual base case	Individual CA variant maximum	Individual TC variant maximum	Parallel base case	Parallel CA variant maximum	Parallel TC variant maximum
1BMA	0.06688	0.2015	0.1998	0.0203	0.06123	0.06067
1BLA	0.06688	0.2015	0.1998	0.0207	0.06241	0.06202
1BTF	0.06687	0.2015	0.1998	0.0129	0.03903	0.03857
2BTF	0.06687	0.2015	0.1998	0.0129	0.03970	0.03867
Silo	0.04172	0.1785	0.1896	0.00001	0.00056	0.00090
1BRT	0.05430	0.1187	0.1181	0.0052	0.01137	0.01137
2BLA	0.05432	0.1188	0.1182	0.0104	0.02274	0.02262
3BLA	0.05432	0.1188	0.1182	0.0104	0.02274	0.02260
4BLA	0.05432	0.1188	0.1182	0.0104	0.02275	0.02259
5BLA	0.05432	0.1188	0.1182	0.0104	0.02272	0.02259
2BMA	0.05431	0.1187	0.1181	0.0076	0.01654	0.01645

the assumed connection to the nearest HCD via large-scale fractures. The similarity with results from the complex model for the semicorrelated and uncorrelated cases thus suggest that the performance measures produced by the complex models are strongly determined by the same factors.

An independent review of the complex model results (Black 2012) suggested that the very sparse fracture density of the hydrogeological DFN model of Follin (2008), in combination with the power-law models for fracture size, yields a model in which connectivity on a large scale depends on a conductive "backbone" of framework of a few very large, discrete fractures. In this type of model, deposition holes are connected to the HCDs only (or with rare exceptions) if they are intersected by a fracture that connects directly to that backbone. The simple series approach used in the SRM amounts to effectively the same assumption.

The difference between the results of the complex model and the simple series-conductor model used here, in the case of perfectly correlated T vs. r, is believed to be an artefact of combining perfect correlation of transmissivity with the highly simplified assumption regarding the second link in each path, namely that this is of length equal to the remaining distance to the HCD, or the maximum fracture radius, whichever is less. The correlation model is effectively:

$$T \propto \sqrt{r} \tag{14}$$

In a two-link path of total length L, this means that the effective series transmissivity of a path with initial fracture radius r_1 will be proportional to:

$$f(r_1) = \frac{\sqrt{r_1}\sqrt{L-r_1}}{\sqrt{r_1} + \sqrt{L-r_1}} \tag{15}$$

A large initial radius will be compensated by a smaller length for the second link, resulting in a narrow range of effective transmissivity. The result for path lengths of L from 600 to 1,000 m is less than an order of magnitude of variation over the possible range of r_1. In a more complex DFN model as used by SKB (2011), the coupling between the transmissivity of the first and second fracture in a given path to the nearest HCD would presumably be less rigid, allowing a wider range of variation in both U_{r1} and F_r.

The close correspondence between an SRM and more complex DFN models might not be reproduced for DFN models in which percolation results from high density of smaller fractures, rather than a few very large fractures acting as a "backbone." However, in such cases, the rock mass might be adequately represented by an ECPM representation, as considered in the SRM for the LILW facility.

For the LILW facility, the vault flows calculated using the SRM are comparable in magnitude to those calculated with complex models for future situations where the Baltic Sea has receded beyond the present location of the current facility and its proposed extension. This builds confidence that the SRM is useful as a reasonable and transparent basis for checking sensitivity of vault flows to main components of the hydraulic system.

The SRM approach provides a simple and transparent way to identify the most significant controls on vault flows in the evaluated system. In the case of the LILW facility, the main controls are the properties of the rock mass, whether small-scale but high-transmissivity zones (PDZs) or relatively high-conductivity ECPM blocks with properties calculated from the DFN model. Both of these are more significant for the relatively shallow, existing vaults than for the deeper proposed expansion, because the part of the recharge–discharge path through the rock mass is proportionally longer for the shallower facility than for the deeper facility.

Concluding remarks

The main purpose of long-term safety analysis for a nuclear waste repository is to show that the proposed siting and selected deposition method can meet requirements on robustness of the barrier system to withstand such features, events and processes that can affect its post-closure performance and requirements on limited discharges of key radionuclides. Hydrogeological analysis is important as input to the assessment of both repository robustness and radionuclide discharges. While complex hydrogeological models are essential in incorporating all observations and site characterization data, including those of shorter-term tests, they also introduce a complexity in the evaluation of uncertainties associated with long-term predictions—for example, questions of conceptual uncertainties can be cumbersome to analyze and the large number of parameters in complex models also lead to a need for an extensive and potentially extensive analysis of the full parameter set.

An SRM does not remove the need for complex site-descriptive models, which are needed for interpretation and integration of site-characterization data, including short-term measurements that cannot always be interpreted with an SRM. Rather, the SRM is derived from complex site-descriptive models that have been calibrated against all such data. Further, the site understanding developed from complex models serves as a basis for identifying features that need to be represented in long-term predictions using the SRM. The SRM is best used to evaluate factors that control early arrivals and migration of the main part of the radionuclide plume, but it has limited usefulness for assessing other details of the plume such as its spatial spread or its long-term tail.

The main motivations for use of an SRM in comparison with complex models are that an SRM (1) is easy to evaluate, (2) is transparent for understanding effects of factors influencing long-term results, (3) readily permits analysis of alternatives for these factors and important variants. In the regulatory setting, SRMs may have a role to play, perhaps even a critical one, when it comes to substantiating the regulatory compliance in regulatory review process. The reasonableness of the results from complex models in the license applications can be checked with the SRM and uncertainties not evaluated by the complex models could also be bounded. This paper presents the development of SRMs for the two cases of SNF and LILW repositories, respectively, at Forsmark. These SRMs have been found valuable for the regulatory evaluation of the results of the complex models that were used in support of the licensing application for these facilities (Lindgren 2017). The reasonableness of the results from complex models in the license applications can be checked with the SRM and uncertainties not evaluated by the complex models could also be bounded. Aside from regulatory use, SRMs could also be used by the licensing applicant as a tool in the safety case to enhance confidence, demonstrate robustness of their predictions, and improve the arguments for regulatory compliance.

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