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Groundwater diversion from a deep-rock repository for spent nuclear fuel: Ecohydrological assessment of environmental impacts

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Abstract. Forsmark in Mideastern Sweden is chosen as site for the planned Swedish deep-rock repository for spent nuclear fuel. The construction, operation and decommissioning of the repository require assessments of various types of risks for health and environment on a wide range of temporal scales. This study is focused on the assessment of environmental impacts during the relatively short construction and operation phases, during which the repository will be kept drained by means of groundwater diversion. This diversion may influence hydrogeological and hydrological conditions and thereby cause ecological and other types of consequences in the surroundings of the repository. We here describe methodology and some main findings from the ecohydrological assessment of consequences for aquatic and terrestrial ecosystems in Forsmark. The assessment combines the results of a number of steps, including ecological field inventories and predictive water-flow modelling. The results of the study show that subsurface disposal of radioactive waste is an important application of ecohydrological concepts in assessments of sites with nature values.

1. INTRODUCTION

The Swedish Nuclear Fuel and Waste Management Co (SKB) is responsible for the management and disposal of radioactive waste from Swedish nuclear power plants. According to the so-called KBS-3 method, copper canisters with a cast-iron insert containing spent nuclear fuel are to be enclosed by bentonite clay and deposited at a depth of approximately 500 metres in granitic bedrock [1]. Some 12,000 tonnes of spent nuclear fuel are forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 6,000 canisters.

The construction, operation and decommissioning of a deep-rock repository require assessments of various types of risks for health and environment. These assessments concern risks on a wide range of temporal scales, such as long-term risks associated with potential post-decommissioning radionuclide releases and subsequent transport towards and within the biosphere [2]. This study is focused on the assessment of environmental impacts, other than radionuclide releases and transport, during the relatively short (less than 100 years) construction and operation phases of the repository. In particular, during these phases the repository will be kept drained by means of groundwater diversion. This diversion may influence the hydrogeological and hydrological system at the site, which in turn could cause ecological and other types of consequences in the surroundings of the repository.

In the following, we describe the methodology used in the Swedish repository programme to predict environmental impacts, in the form of ecological consequences that may be caused by groundwater diversion during construction and operation of a deep-rock repository. The methodology is illustrated using data and information from Forsmark in Mideastern Sweden. Forsmark, which is chosen by SKB as site for the planned repository, is very valuable from a nature conservation point of view. The assessment methodology requires data and information on site-specific ecological, hydrogeological and hydrological factors, as well as profound understanding of interactions between such factors. Specifically, the methodology comprises the following overall steps, to be described in more detail in subsequent sections:

- Geographical delineation and nature-value classification of nature objects at the considered site.
- Assessment of the sensitivity of delineated nature objects and their associated species to changes of the hydrogeological and hydrological conditions.
- Prediction of hydrogeological and hydrological effects due to the groundwater diversion from the deep-rock repository.
- Integration of ecological, hydrogeological and hydrological results for (ecohydrological) assessment of environmental impacts, in terms of ecological consequences.

2. STUDY SITE AND METHODS

2.1 The Forsmark site

Forsmark is located in Mideastern Sweden on the coast of the Baltic Sea, some 120 km north of Stockholm, Sweden's capital city. Extensive, multidisciplinary site investigations, processing of emerging data and site-descriptive modelling were performed during the period 2002–2008 [3, 4]. Forsmark contains small wetlands (e.g. rich fens and lime-rich ponds) and rich coniferous forests located on lime-rich soil, hosting species that are considered to be worthy of protection. The high nature values of Forsmark are the result of the site's near-coastal location, flat topography, fast shoreline displacement, and small but important height variations. Other important factors are the lime-rich soil, the geographical location at a boundary between typical northern and southern nature types of Sweden, and a relatively undisturbed location.

The regolith (i.e. unconsolidated deposits overlying the bedrock) at the site is dominated by relatively permeable till [5]. The groundwater table is shallow and generally follows the ground-surface topography, giving rise to small-scale groundwater flow systems near the ground surface that overlie larger-scale flow systems in the bedrock [6]. The shallow bedrock (upper c. 150 m) contains a well-connected network of geological structures, consisting of so-called sheet joints (geological structures that may have high horizontal permeability) and steep fracture zones that locally are in contact with the regolith [7].

The subsurface part of the planned repository consists of a spiral-shaped access ramp and vertical shafts, a central area (containing rock caverns) and a repository area with tunnels for deposition of canisters at a depth of almost approximately 500 metres [8]. The total tunnel length will be some 70 kilometres, and the construction, operation and decommissioning phases will comprise a total time period of 60–70 years. During the construction and operation phases the access ramp, the central area and the shafts will be open. During repository operation, different deposition tunnels in the repository area will be successively constructed, used for canister deposition and thereafter backfilled. Hence, all deposition tunnels will not be open simultaneously at any point in time.

2.2 Delineation and classification of nature objects

A key component of the assessment methodology is the performance of field inventories for delineation and classification of objects with nature values (here denoted nature objects). Preparatory work for the delineation and classification at Forsmark included e.g. studies of air photographs and different types of maps for identification of areas having prerequisites for high nature values. Comprehensive ecological field inventories were subsequently performed in an investigation area covering some 10 km^2 [9]. According to established practice in Sweden, the following system was used for classification of nature values at the site:

- Class 1 – National value.
- Class 2 – Regional value.

- Class 3 – Municipal value.
- Class 4 – Local value.

The object-specific classifications take into account factors such as rarity of nature types (including the presence of Natura 2000 nature types according to the EU framework) and rarity of species (including occurrences of red-listed and/or legally protected species). Moreover, the classifications consider size and spatial continuity of delineated objects, ecological relations with neighbouring objects, and the presence of ecologically important structures or functions. It should be emphasized that nature-value classifications are not completely objective. Rather, they should be considered as expert judgements that require many years of practical experience.

2.3 Sensitivity of nature objects

The second step of the methodology is to classify delineated objects according to their sensitivity to changes of the hydrogeological and/or hydrological conditions. Specifically, the purpose is to define object-specific hydrogeological/hydrological threshold values for nature-type transitions and losses of nature values. The sensitivity is related to water-supply mechanisms and water balances, which in turn are governed by topographical, meteorological, hydrogeological and other factors that collectively contribute to the ecological status (e.g. nature type, vegetation and fauna) of an object. For instance, the sensitivity to groundwater diversion from the bedrock may be lower if low-permeable regolith (e.g. glacial clay) is present below an object as a barrier to reduce or even prevent groundwater-table drawdown.

Specific field investigations were performed in Forsmark to characterize the spatial distribution of different regolith types at delineated objects, and to enable long-term monitoring of groundwater levels and surface-water levels [10, 11]. These investigations provided object-specific data and supplement the regional-scale conceptual models of regolith distribution and near-surface hydrogeology [5, 6]. Moreover, detailed water-flow modelling of individual nature objects were performed to gain further insight into water-supply mechanisms and water balances [12]. Existing experience-based knowledge (e.g. [13]) regarding the ecohydrological prerequisites for different nature types and species in Sweden was an important input to define the following sensitivity classes for the Forsmark study:

- Class 1 – Very high sensitivity. For objects in this class, ecological consequences can occur if the groundwater-table drawdown is 0.1 m or larger. Examples include ponds and fens without low-permeable bottom sediments.
- Class 2 – High sensitivity. For objects in this class, ecological consequences can occur if the groundwater-table drawdown is 0.1–0.3 m. Examples include ponds and fens that are underlain by low-permeable bottom sediments.
- Class 3 – Sensitive. For objects in this class, ecological consequences can occur if the groundwater-table drawdown is 0.3–1 m. Typical examples of this class are moist forests and shore meadows.
- Class 4 – Less sensitive. For objects in this class, ecological consequences can occur if the groundwater-table drawdown is 1–2 m. This class includes e.g. fresh forests.
- Class 5 – Not sensitive. For objects in this class, drawdown of the groundwater table cannot lead to any negative ecological consequences. This class includes e.g. dry forests.

2.4 Prediction of hydrogeological and hydrological effects

The third step is to predict effects on hydrogeological and hydrological conditions at individual nature objects due to groundwater diversion from the deep-rock repository. In the present study, the numerical water-flow modelling tool MIKE SHE [14] was used to predict effects on groundwater levels, the level of the groundwater table, surface-water levels, and discharges in streams. Specifically, the geometry and the reduced pressure of the subsurface part of the repository were implemented into a site-specific MIKE SHE model that represents the integrated groundwater-surface water flow system, including groundwater in both regolith and bedrock [15, 16]. Transient model calibration was performed prior to the predictive modelling, using both long-term (undisturbed) monitoring data and data obtained from hydraulic (pumping) tests [6, 16].

Different MIKE SHE simulation cases were defined to represent different future situations, for instance in terms of the number of open repository tunnels. Moreover, simulations were performed for different hydraulic-conductivity values for the grouted bedrock around subsurface cavities. The conservative simulation case that was chosen to provide input to the integrated ecohydrological assessment represents a purely hypothetical situation, with a fully open repository and a relatively permeable grouted zone. The MIKE SHE calculations resulted in sets of continuous "maps" of e.g. groundwater-table drawdown at the site, as well as supporting data for object-specific assessments such as surface-water level drawdown of individual lakes and wetlands.

2.5 Assessment of environmental impacts

The last step of the methodology is to use the combined results of the previous steps to assess environmental impacts (ecological consequences) for individual nature objects and their associated species. The use of consequence classes facilitates prioritization and development of protection-, mitigation- and compensation measures for individual nature objects and/or species. There is no standard system in Sweden for classification of ecological consequences, and such classifications are by necessity based on a mixture of quantitative and qualitative information [17]. The classification system used in this study considers consequences of reduced availability of groundwater and/or surface water, also taking into account nature values and the ecological status of individual objects and species [18]:

- Class 1 – Very large consequences. This class means extinction of ecological core values for a nature object of value class 1, or extinction of core values of an assigned Natura 2000 area.
- Class 2 – Large consequences. This class involves, for instance, substantial ecological changes of a nature object of value class 2.
- Class 3 – Noticeable consequences. This class involves, for instance, extinction of the nature values of a nature object of value class 3.
- Class 4 – Small consequences. This class involves, for instance, extinction of the nature values of a nature object of value class 4.
- Class 5 – Insignificant consequences.

3. RESULTS OF THE FORSMARK ASSESSMENT

3.1 Delineation, classification and sensitivity of nature objects

At the Forsmark site, totally 134 nature objects are geographically delineated and classified according to their nature values. These objects include 79 wetland objects, 49 forest objects and six lakes. Ten of the 79 wetland objects are classified as class 1 (national value), 26 as class 2 (regional value), whereas the remaining 43 objects hence are classified as class 3 or 4 (municipal or local value). One of the 49 forest objects is classified as class 1 and 23 objects as class 2. Specifically, the objects with the highest nature values in Forsmark include rich fens, lime-rich ponds, and rich coniferous forests located on lime-rich soils. Many of these objects provide habitats for red-listed species, such as orchids and lime-favoured fungi in forests. Moreover, some of the delineated wetlands contain the rare species pool frog (*Rana lessonae*) and fen orchid (*Liparis loeselii*), which are protected according to Swedish law (Species Protection Ordinance).

According to field investigations, the bottom of many wetlands consists completely or at least partially of low-permeable glacial clay. However, most of the delineated forest objects are located in till areas absent of low-permeable regolith. Hence, most forest objects do not have any barrier that reduces or prevents drawdown of the groundwater table in case of groundwater-level drawdown in the underlying bedrock.

3.2 Prediction of hydrogeological and hydrological effects

According to the conceptual hydrogeological model of the site, groundwater diversion from the bedrock yields groundwater-level drawdown in shallow-rock sheet joints [7]. In accordance with this conceptual model, the MIKE SHE calculations show that the groundwater diversion from the repository may result in groundwater-level drawdown in the bedrock in relatively large areas [15]. However, the modelling results show that the groundwater-table drawdown will be rather limited geographically. In particular, the results illustrate that drawdown of the groundwater table primarily will occur in areas with permeable, steep fracture zones in contact with the regolith.

The MIKE SHE simulation case that represents a fully open repository with a permeable grouted zone shows an influence area for the groundwater-table drawdown that is 2.5 km^2 in size, which is less than the areal extent (3–4 km^2) of the subsurface part of the repository [8, 15]. According to the model calculations the groundwater diversion will generally lead to insignificant drawdown of surface-water levels of lakes, and it will have small effects on stream discharges.

3.3 Assessment of environmental impacts

Based on the specified MIKE SHE simulation case (see above), the results of the ecohydrological assessment show that without mitigating measures, the groundwater diversion may lead to very large consequences (i.e. consequence class 1) for terrestrial ecosystems in the form of two wetland objects with national value (class 1). These two objects consist of the two Natura 2000 types rich fens and lime-rich oligo-mesotrophic waters with benthic vegetation [18]. Moreover, ecological consequences may be large (consequence class 2) for 15 wetland objects with national or regional value. The assessment shows that there may be very large consequences for some of the red-listed species that exist at the site, including fen orchid and pool frog that also are legally protected.

Compared to wetlands, forests and forest species of Sweden are generally less sensitive to changes of the level of the groundwater table. Accordingly, the Forsmark assessment results show that consequences for delineated forest objects only will be noticeable or smaller, and that there will be only noticeable consequences for red-listed fungi in forests. It is predicted that the groundwater diversion will lead to insignificant or small ecological consequences for aquatic ecosystems at the site, due to their relatively limited nature values and the small hydrological effects on such systems. There is an assigned Natura 2000 area in the neighbourhood of the Forsmark site investigation area. According to the results of the assessment, protected habitats and species in this area will not be harmed or subject to any disturbance that significantly render difficult preservation of outpointed species.

4. DISCUSSION

This study illustrates that subsurface disposal of radioactive waste is an important application of ecohydrological concepts in environmental assessments of sites with nature values. SKB's deep-repository permit application according to the Swedish Environmental Code, and the associated EIA (Environmental Impact Assessment) document, propose mitigating measures in the form of preparedness for artificial water supply to wetlands in Forsmark, in order to preserve nature values and species. The underlying idea is that this method shall eliminate any potential negative consequences of the groundwater diversion for wetlands that are habitats for rare species, such as pool frog and fen orchid [19]. The existing monitoring programme in Forsmark includes e.g. ecology, hydrogeology, and hydrology. This programme will continue and it will also undergo further developments as part of preparations for the coming repository construction and operation, and the associated groundwater diversion.

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