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Probabilistic assessment of the influence of lake properties in long-term radiation doses to humans

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The assessment processes concerning the safety of nuclear waste repositories include the modelling of radionuclide transport in biosphere and the evaluation of the doses to the most affected humans. In this paper, a scenario, in which a contaminated lake is the water source for drinking water, irrigation water and watering of livestock, is presented. The objective of the paper is to probabilistically study the influence of lake properties as parameters in the assessment scenario. The properties of the lake are a result of previously conducted probabilistic studies, where the land uplift of the terrain surrounding the repositories and the formation of water bodies were studied in a 10,000-year time span using Monte Carlo simulation. The lake is formed at 3000 years from present day and the changing properties of the lake have been used in the study. The studied radionuclides ^{36}Cl, ^{135}Cs, ^{129}I, ^{237}Np, ^{90}Sr, ^{99}Tc and ^{238}U enter the lake with a rate of 1 Bq/year. The transport process from the lake water to humans is described and the doses (dose conversion factors) to adult humans are evaluated based on a study on average food consumption. Sensitivity analysis is used for identifying the parameters having the most influence on the outcome of the dose. Based on the results from the sensitivity analysis, the volumetric outflow rate of the lake and the volume of the lake were taken into closer consideration. The results show the influence of probabilistically derived geomorphic lake input parameters on the dose.

1. Introduction

Modelling of radionuclide transport in biosphere is important when evaluating the safety of repositories for spent nuclear fuel. In Finland, a spent nuclear fuel repository is currently being built into the bedrock of the Olkiluoto Island, situated in the western part of Finland. The size of the island is approximately 12 km^2. Finnish Radiation and Nuclear Safety Authority (STUK) regulates the use of nuclear energy in Finland and it is stated in the Guide for Disposal of Nuclear Waste (STUK, 2014) that when assessing compliance with the dose constraints, it is assumed that radioactive release occurs at the repository and that the radionuclides are transported to the surface environment by groundwater. A lake shall be considered as a recipient of these releases. Also, at least the following exposure modes shall be considered:

– The use of contaminated water as household and irrigation water as well as for drinking water for animals, and
– The use of contaminated natural or agricultural products originating from terrestrial or aquatic environments.

The latest state-of-the-art biosphere assessment for the Olkiluoto site is presented in Posiva (2013a). Their radionuclide transport and dose models consist of several sub models, comprising hundreds of components with respective parameters and transfer coefficients, making it difficult for the authorities to perform independent verification of the modelling results. Also, running comprehensive uncertainty and sensitivity analyses, often considered necessary for improving the confidence in the model results (e.g., Thiessen et al. (1999)), does not seem feasible. In most cases probabilistic modelling has not been done in terms of safety case assessment for nuclear waste disposal. One exception is the Canadian nuclear waste disposal safety case (Bird et al., 1993; Keith Reid and Corbett, 1993) where the biosphere modelling is thoroughly probabilistic. In (STUK, 2014) probabilistic modelling is not required but it is stated that the significance of uncertainties in the safety case should be assessed by using appropriate methods. The present research effort has been initiated to produce alternative

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biosphere models easier lending themselves to such an evaluation.

In modelling, there is always a trade-off between computational complexity and comprehensiveness of the models. Therefore, also more stylized models should be used, although both stylized approaches and sophisticated ones have their merits (e.g., (Ikonen, 2015)). In (Walke et al., 2015; Wörman et al., 2004; IAEA, 2003; Larsson et al., 2002; Thiessen et al., 1999) the use of several models, simple and complex ones, for defining the order of magnitude in dose conversion factors in specific situations are discussed. The present study contributes to the study of more stylized models to represent the various components of the biosphere, with a specific aim to explore the sensitivity of the dose results to various factors involved in the modelling.

Two alternative approaches can, in principle, be taken to perform the sensitivity analysis and model reduction: either the model can be implemented in the whole and the model parameters can be varied to study their influence on the modelling results, or the model can be divided into sub models and each sub model can be analyzed and optimized separately. The first approach is in many cases computationally demanding and becomes unfeasible for large models. On the other hand, this approach easier allows taking into account the possibly complex interrelations between the various parts of the model. The sub model approach is computationally simpler and allows an extensive set of results on the effects of the model parameters to be produced, but on the cost of more demanding interpretation of the meaning of the results.

Simpler radionuclide transport models have been implemented for several purposes also in the Finnish repository safety analyses. For example, in (Vieno and Suolanen, 1991) different scenarios for radionuclide release in a lake, sea or a well are considered. In (Vieno, 1994) a scenario for a drinking water well is presented where the dose conversion factors for different radionuclides are simply calculated based on the effective dilution volume of the well and the intake rate of water. In (Hjerpe and Broed, 2010) the simple well scenario is extended to consider not only the drinking water to people but also household use of the well water, as well as using it for irrigating crops and watering livestock. In (Kupiainen, 2014) simplification of the radionuclide release and transport models is presented by means of statistical analysis of the parameters and the model behavior.

In (Avila et al., 2013) the long-term transport and accumulation of radionuclides is examined based on a landscape development model, similar to that used in Posiva (2013a), and the results are presented for the next 9000 years. Their study site, Forsmark at the eastern coast of Sweden, is affected by the post-glacial land uplift exhibiting approximately the same present yearly rate as in the Olkiluoto area (i.e., 6 mm/year). Their results identify especially liquid-solid distribution coefficients and concentration ratios from soil to plants as key contributors to the dose estimates.

In (Pinedo et al., 1999) several nuclear waste disposal assessment scenarios from different countries were presented. The effect of volumetric outflow rate on the doses to humans and the changes due to varying outflow rates are discussed in the paper. This is also a basis for this study: to find out how the lake parameters, especially the outflow rate and the volume of the lake, influence the total doses.

In this paper, we present a modelling scenario based on the agricultural well concept presented in Hjerpe and Broed (2010) with the change that the water source has been changed from a well to a lake. The information about the lake is based on a probabilistic study of the development of the geomorphic landscape in the Olkiluoto region during the following 10,000 years (Pohjola, 2014; Pohjola et al., 2014). In that study, a probabilistic digital terrain model was created using available ground elevation and water depth measurement data. The uncertainties of the measurement data were taken into account, and 100 realizations of the land and sea bottom surfaces were created inside the confidence limits of the model using Monte Carlo simulation. Due to the depression caused by the most recent glacial period, the Weichselian ice age, the bedrock in Finland is still rebounding towards the unloaded position. The parameters in an empirical land uplift model (Påsse, 2001), based on fitting a mathematical function to lake isolation and now also archaeological data, was optimized probabilistically. The lake isolation data indicates, by using the corrected ^{14}C radiocarbon dating method, at what time was a particular lake isolated from the sea. The probabilistic digital terrain model and the probabilistically fitted land uplift model were combined using a GIS-based toolbox UNTAMO (Posiva, 2013b) to estimate the formation of surface water bodies in the area. Out of these results, one lake was selected for the present study. Due to the probabilistic approach in the terrain and land uplift modelling, the characteristics of the lake are presented in the form of distributions including 100 realizations for each 1000-year time step. The use of these distributions as inputs to the radionuclide transport and dose calculation model allows the study of the sensitivity of dose conversion factors to lake properties such as lake volume [m^3] and volumetric outflow rate [m^3/year] in a context of long-term environmental change. In the structure of this paper, the components of the BIOMASS reference biospheres methodology (IAEA, 2003) have been applied.

2. Assessment context

The guide on safety of nuclear waste disposal provided by the Finnish regulator (STUK, 2014) is used to set the regulatory context in this study. However, this study has been conceived to explore the methodology, not to be interpreted as a part of any specific repository safety case per se. The dose assessment in this paper considers a future lake to be formed near the nuclear waste repositories at Olkiluoto, and the purpose is to study the sensitivity of the dose results to the variability in the parameter values, especially in those related to the properties of the lake. Following from the regulatory guide, the time window for the dose calculations is set to 10,000 years (similarly to e.g. (Posiva, 2013a)) to cover the “assessment period, during which the radiation exposure of humans can be assessed with sufficient reliability, and which shall extend, at a minimum, over several millennia”. Due to the inherent uncertainties in the analysis of such a long periods, climate, ecosystems, human habits, diet and metabolism are assumed to be similar to those at present, as advised in the regulatory guide (STUK, 2014). Radionuclides postulated to be released from the repository are assumed to enter the lake water directly (i.e. the retention potential of the bottom sediment is ignored here) with a release rate of 1 Bq/year of each nuclide (^{36}Cl, ^{135}Cs, ^{129}I, ^{237}Np, ^{90}Sr, ^{99}Tc and ^{238}U). The chosen suite of radionuclides covers a range of biogeochemical behavior and includes nuclides both in earlier assessments for the site (e.g. Vieno and Suolanen (1991); Posiva (2013a)) and of general interest (e.g. Chen et al. (2006)). The ingrowth of radioactive daughters of ^{238}U has not been taken into consideration as the long time frame of the study would make it negligible. The lake will be formed in between 3000 and 4000 AP (years after present) due to changes in the geomorphic landscape caused by the post-glacial uplift. The properties of the lake in 3000 AP and 10,000 AP are presented in Table 1. Lake volume, area, water exchange rate and mean depth are given as mean values and standard deviations of the corresponding distributions obtained from the probabilistic landscape development model (Pohjola, 2014). The probability of the location of the studied lake is presented in Fig. 1. The figure indicates that, based on the landscape development model, the lake will be formed with 100% certainty