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Influence of climate on landscape characteristics in safety assessments of repositories for radioactive wastes

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A B S T R A C T

In safety assessments of repositories for radioactive wastes, large spatial and temporal scales have to be considered when developing an approach to risk calculations. A wide range of different types of information may be required. Local to the site of interest, temperature and precipitation data may be used to determine the erosional regime (which may also be conditioned by the vegetation characteristics adopted, based both on climatic and other considerations). However, geomorphological changes may be governed by regional rather than local considerations, e.g. alteration of river base levels, river capture and drainage network reorganisation, or the progression of an ice sheet or valley glacier across the site. The regional climate is in turn governed by the global climate.

In this work, a commentary is presented on the types of climate models that can be used to develop projections of climate change for use in post-closure radiological impact assessments of geological repositories for radioactive wastes. These models include both Atmosphere-Ocean General Circulation Models and Earth Models of Intermediate Complexity. The relevant outputs available from these models are identified and consideration is given to how these outputs may be used to inform projections of landscape development. Issues of spatial and temporal downscaling of climate model outputs to meet the requirements of local-scale landscape development modelling are also addressed. An example is given of how climate change and landscape development influence the radiological impact of radionuclides potentially released from the deep geological disposal facility for spent nuclear fuel that SKB (the Swedish Nuclear Fuel and Waste Management Company) proposes to construct at Forsmark, Sweden.

1. Introduction

Whereas climate models operate at global to regional scales (with grid resolutions that typically range from a few hundred kilometres down to about 10 km, see Chapter 9 of IPCC, 2013), landscape development models typically operate at regional to local scales (i.e. from tens of kilometres down to tens of metres). Though there are numerous climate-controlled processes involved in landscape change, the development of ice sheets, where they occur, has the most dramatic and widespread effects over a range of timescales. Shorter-term (sub-millennial) effects may include accelerated episodes of erosion and broadening of valleys, redistribution of large amounts of mass (e.g. in the form of moraines), the eroding of over-deepened valleys and changes in the flow directions of rivers. On longer (multi-millennial) time scales, the isostatic response of the lithosphere in the vicinity of ice sheets may be of importance as it leads to a downward movement of the lithosphere during ice-sheet growth and to uplift during ice-sheet decay and possibly long after the ice sheet has disappeared.

Permafrost development, where it occurs, is also a regional-scale phenomenon, but it can often be modelled at a local-scale. A commonality with ice-sheet and large-scale geomorphological modelling is that permafrost modelling can be undertaken using long-term average climatic characteristics as boundary conditions.

It is important to emphasise that the modelling of climate and its impacts on the landscape necessarily involve substantial simplifications. Thus, for example, feedbacks between ice-sheet development and climate are not always fully taken into account, the effects of ice-fabric structure on ice-sheet viscosity and flow are not yet included in most models, and sub-glacial hydrology is either not represented or is treated in a very simple way. Various models typically adopt alternative simplifications. Thus, it is often

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appropriate to make projections using an ensemble of models to explore the uncertainties inherent in adopting different conceptual models that simplify the real world situation of interest in various ways.

At coastal locations, both climate and sea level are strong determinants of coastal processes, such as cliff erosion and inundation. However, changes in sea level can also have effects inland. Specifically, as sea level changes, rivers will adjust to the altered sea level. This process may require tens of thousands to millions of years, so river profiles will tend to lag behind sea-level changes. The long-term geomorphological evolution of catchments under altered climatic conditions and sea-level changes is an important area to which long-term climate model outputs can be applied. Thus, aspects such as river cutback and stream capture may affect the overall geometry and detailed characteristics of the surface-water system. Generalised erosion may lower interfluves, whereas incision may deepen river valleys. In this context, both climatic conditions and sea-level changes may play important roles.

Post-closure radiological impact assessments of geological disposal facilities for radioactive wastes typically extend to cover periods of thousands to hundreds of thousands of years after closure of the facility (e.g. RWMD, 2010; SKB, 2011). For shallow disposal facilities the relevant timescale may be rather shorter, but the susceptibility to changes in climate and landform may be considerably greater (LLWR, 2011). Assessments over such timescales are in line with international recommendations (e.g. IAEA, 2011). Over such timescales, both climatic conditions and the landscape at the radioactive waste disposal facility are expected to alter to a sufficient degree that such changes need to be taken into account in the radiological impact assessment (LLWR, 2011; SKB, 2011). It is not possible to predict future changes in climate and landscape over such timescales. However, it is possible to develop a set of scenarios (i.e. qualitatively or quantitatively distinct narratives of future changes) for a disposal facility site that explore a range of possible long-term variations in climate and landscape. This approach allows the development of a set of assessment calculations consistent with those scenarios that can be used to explore the range of time-dependent radiological impacts that could arise from disposal of long-lived radioactive wastes in such a disposal facility (SKB, 2011; Kautsky et al., 2013b; Lindborg et al., 2013; Näslund et al., 2013).

The issue of how to represent climate change and landscape development in post-closure radiological impact assessments is of growing interest. It was explored in detail in the IAEA-sponsored BIOMASS programme (BIOMASS, 2003) and in the EU-funded BIOCLIM programme (BIOCLIM, 2004). Further consideration was given to environmental change issues in post-closure repository safety assessment in the IAEA EMRAS II programme (IAEA, 2012). More recently, an international BIOPROTA programme relating to the near-surface environment has been taking into consideration the effects of climate change and landscape development on this component of the repository environment (Smith et al., 2014).

In parallel, with the BIOPROTA project, Working Group (WG6) of the IAEA-sponsored MODARIA programme (http://www-ns.iaea.org/projects/modaria/) is providing a common framework for addressing environmental change in long-term safety assessments of disposal facilities for solid radioactive wastes. In this context, climate and climate change is considered to be an important factor determining landscape development. In turn, the changing landscape can influence the transport of radionuclides from a disposal facility, the degree to which those radionuclides are accumulated in the accessible environment, and the extent of utilisation of that environment by humans and other organisms. Ideally, a deep geological repository would be completely isolated from the accessible environment and immune from the effects of landscape change, but this will seldom, if ever, be possible. For near-surface facilities, changes in the landscape will almost always need to be taken into account, unless only short-lived radioactive wastes are disposed. Even in this case, such short-lived wastes often contain sufficient quantities of long-lived radionuclides as to require that safety assessments extend to periods of thousands of years. The WG6 programme of work consolidates the history of methodological developments mentioned above, while bringing into focus the latest developments in climate-change science and assessment techniques.

The work reported in this paper has been undertaken in support of the MODARIA WG6 programme. In this study, an account of the linkages from models of climate and climate change to representations of landscape development is provided. As such linkages are particularly strong and complex in colder regions (whether determined by latitude or altitude) affected by permafrost and ice-sheet development, and because several of the most advanced programmes for repository development are located in those regions, these cold-region aspects are emphasised in this commentary. It is being published to bring on-going work in this area to the attention of researchers and safety assessment specialists in the field of environmental radioactivity, not least because much of the information used and some of the modelling approaches adopted may be useful for those involved in managing and assessing the long-term radiological safety of sites contaminated with radioactive wastes and liabilities arising, for example, from former uranium mining and milling activities.

2. The overall relationship between climate and landscape and outputs that may be obtained from climate models

Earth is a dynamic planet and every point on its surface is subject to continuous changes in elevation. These changes are due to tectonic uplift, erosion and other processes, and the rates at which they occur may vary over several orders of magnitude at different locations (Selby, 1985). Examples of such changes are erosion and sedimentation due to fluvial processes in a river system (including both meandering and downcutting, as well as the infilling of lakes), glacial erosion and the over-deepening of subglacial valleys, and isostatic rebound due to unloading of the crust by, e.g. the melting of ice sheets (see, for example, SKB, 2010a). While fluvial erosion is often observable in the short-term (though it can continue over many thousands of years) and depends strongly on the amount and intensity of precipitation, as well as on topographic factors, isostatic rebound occurs rather slowly over thousands or tens of thousands of years and depends on, among other factors, the growth and decay of ice sheets (which in turn are determined by time-varying regional patterns of temperature and precipitation), and the rheological characteristics of the lithosphere and asthenosphere (McConnell, 1968; Hagdorn, 2003). Even from these simple examples, it is immediately obvious that recurring patterns of climate change and alterations in the landscape are closely interlinked, and that they can have an impact on repository safety. A change in climate may cause increased or decreased precipitation/evapotranspiration (BIOCLIM, 2004) and, in more extreme cases, an increase or decrease in the volume and distribution of ice sheets, ice caps and glaciers (Hagdorn, 2003; SKB, 2010a; Näslund et al., 2013). Both the persistence of particular climatic conditions and changes in climate with time will inevitably lead to various changes in the landscape expressed on timescales ranging from a few hours (for a single extreme climatic event) to many thousands, or even millions of years. During stable climatic conditions, landscape changes are often slow and reasonably