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Representation of the biosphere in post-closure assessments for the UK geological disposal programme

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ABSTRACT

This paper gives an overview of the Nuclear Decommissioning Authority, Radioactive Waste Management Directorate approach to representing the biosphere in post-closure safety assessment studies. The assessments consider potential releases of radionuclides and chemically toxic substances from a geological disposal facility that may reach the biosphere by transport in groundwater and gas. It gives an outline of the key processes and understanding underpinning the representation of the biosphere and how the biosphere may evolve over the long timescales of relevance to post-closure safety. The current biosphere assessment approach and associated models are supported by research studies and collaboration that ensure they are consistent with international recommendations. Research studies are also commissioned to reduce uncertainty surrounding key contaminants and potential exposure pathways and to help ensure that the approach and models are adaptable and flexible enough to incorporate future developments, as the geological disposal programme moves towards site selection.

Keywords: potentially exposed group, climate change, carbon-14.

Introduction

The biosphere consists of the atmosphere, surface and near-surface environment, normally inhabited by living organisms, including any near-surface aquifers (Fig. 1). It acts as the receptor for any geological disposal facility (GDF) derived contaminants that may be migrate through the geosphere in groundwater and gas. The transport and distribution of radionuclide fluxes through the biosphere is represented so that concentrations in environmental media (e.g. soil) can be estimated. In turn, these concentrations are used to estimate the radiation exposures of humans, focussing on potentially exposed groups (PEGs) within the population. Over recent years, increased consideration has been given to the need to demonstrate that the environment as a whole is also adequately protected against adverse effects from the GDF. For this reason, the Nuclear Decommissioning Authority, Radioactive Waste Management Directorate (NDA RWMD) have been considering the potential impacts on non-human biota (SKM Enviros, 2011). Consideration is also given to the potential releases of chemotoxic substances from a GDF (Wilson *et al*., 2011).

Importance of the biosphere

One important consideration in post-closure safety assessments is the long timescales, of hundreds of thousands of years. This means that, from the outset, the NDA RWMD biosphere research and assessment programme has included consideration of issues relating to climate change and landform evolution. It has used the internationally agreed methodology BIOMASS (International Atomic Energy Agency, 2003) as

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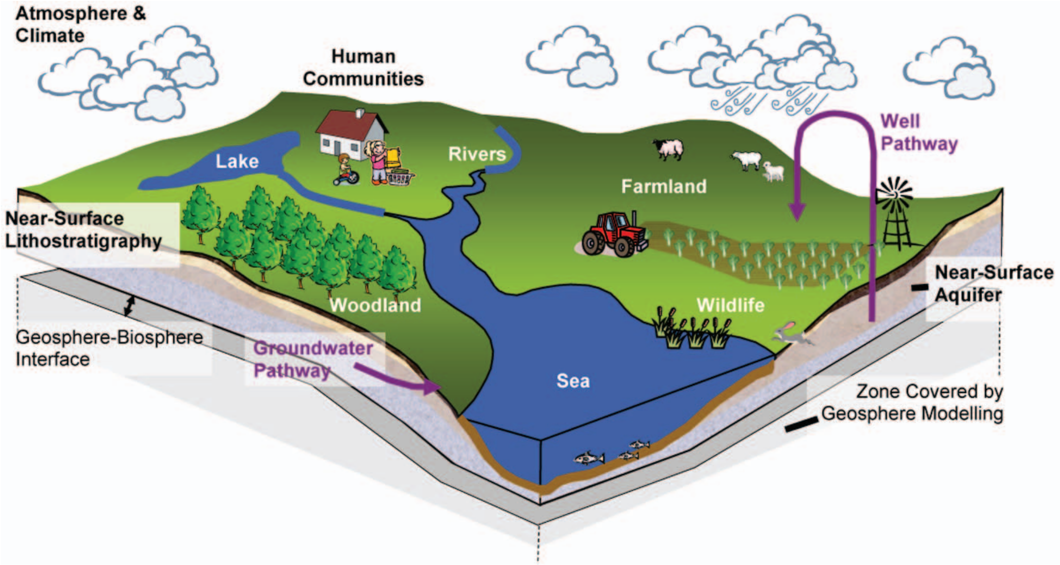

FIG. 1. Components of the biosphere.

guidance for defining evolving biosphere systems for use in post-closure performance assessments.

The evolution of the physical biosphere encompasses climate change and landform changes, which include changes to sea level, river courses, surface water bodies and surface topography. These provide boundary conditions for the groundwater flow field. Therefore, the evolution of the biosphere can have a direct impact on groundwater flow in the geosphere and hence on the migration of radionuclides via the groundwater and gas pathways. Along with the near-field model and representation of the geosphere, the biosphere forms an important component of the top level model in the NDA RWMD hierarchy of models that is used to carry out safety assessment modelling of the GDF (Nuclear Decommissioning Authority, 2010*a*).

Regulatory guidance on geological disposal that relates to the consideration of the biosphere emphasizes that the results of quantitative assessments can only be regarded as broad indicators of environmental safety and not as predictions of actual impact (Egan, 2009). Nevertheless, the primary assessment endpoint for the purpose of guiding decision-making is described as annual individual radiological risk, which is to be compared against the risk guidance level given by the environment agencies (Environment Agency and Northern Ireland Environment Agency, 2009). In terms of assessing impacts on non-human biota and chemotoxic substances, the regulatory regimes reflect the developing international recommendations and are not, as yet, well defined.

Approach to biosphere modelling

The NDA RWMD approach to representing the biosphere in assessing releases from a GDF is described in the *Biosphere Status Report* (Nuclear Decommissioning Authority, 2010*b*). It aligns with international guidance, notably the BIOMASS methodology (International Atomic Energy Agency, 2003), which sets out a structured approach to defining reference biosphere systems that can then be used as a basis for undertaking assessment calculations. The approach considers alternative climate scenarios derived from sequences of future climate that were explored in detail in the BIOCLIM project (BIOCLIM, 2004).

For evaluating the effect on human health due to releases of radionuclides, annual effective risk to a representative member of the PEG is calculated for comparison against the regulatory guidance level. In terms of societal change, it is assumed that habits, behaviour and metabolic characteristics are similar to those observed in present-day populations, though not necessarily at the site (e.g. from analogue regions if climatic conditions that differ from those at the present-day are being addressed). Major advances or regression in technology are not assumed to occur.

Primarily, PEG characteristics are defined based on generalized habits data. Consideration is given to PEG characteristics for a range of climatic conditions, with the base case being temperate conditions. Alternative groups are considered based on farming communities making reasonably maximized use of local resources, including a well drilled into a local aquifer. These consist of adults, children and infants in two different settings, an inland community and a coastal community. It is assumed that members of each PEG derive their foodstuffs and drinking water from a land area of 10 km^2, centred on the location of highest radionuclide concentration. This area is based on that required for a small agricultural community supporting about 300 people, which is adopted as the basis for assessment.

The identification and characterization of PEGs at a site-specific level has to be developed for continuously evolving climatic and landscape conditions, including their associated human community structures. The various PEGs are identified in qualitative terms and can be broadly characterized for a number of scenarios ranging from a present-day community in a temperate climate, with present environment and land use pattern, to a primitive community in a boreal climate, with a low population density in a wooded landscape. A detailed discussion of the protocol for deriving these scenarios is given in Thorne and Kane (2006).

The biosphere assessment model for the groundwater pathway includes a two-layer representation of the soil zone that is parameterized using hydrological characteristics for broad classes of soils of the British Isles. The assessment model includes all radionuclides and radionuclide decay chains that are included in the UK National Radioactive Waste Inventory. The soil model is coupled with a simple plant-animal model and includes consideration of exposure pathways to the PEG from ingestion of local crops, animal products, drinking water, inhalation of dust, external irradiation from contaminated land, inadvertent ingestion of soil and ingestion of fish sourced from contaminated water.

The exposure routes are used to make separate calculations for well abstraction and natural groundwater discharge, and these two sets of results are combined to provide an overall set of biosphere dose conversion factors. These are then are used in combination with calculated fluxes in groundwater from the geosphere to provide effective doses and associated risks.

A spreadsheet-based model was initially adopted for representing the biosphere processes with the calculations carried out at equilibrium for an indefinitely maintained input radionuclide flux or concentration (Thorne, 2007). That model was also adapted to calculate concentrations of chemically toxic contaminants in environmental media (Wilson *et al*., 2011). The dynamic form of the mathematical model has now been implemented in *GoldSim* (GoldSim Technology Group, 2010) which is the simulation package NDA RWMD have adopted for the majority of the top level model calculations. Features of the biosphere model are illustrated in Fig. 2.

At this site-generic stage of development, no detailed information on a site-specific biosphere is available. Even after a site has been selected and characterized, there will still be considerable uncertainty in the characteristics of the biosphere at times in the far future when any contaminant releases from a GDF would reach the accessible environment. These uncertainties include natural changes in landscape driven by climate processes and changes in the way people might interact with the biosphere (e.g. the relevant types of agriculture).

Consideration of natural variations in insolation indicates that the present interglacial period will extend for up to 50,000 years (Loutre and Berger, 2000). Including consideration of greenhouse gases from the combustion of fossil fuels extends the present interglacial to beyond 100,000 years. Based on these projections, the climate of the British Isles will initially develop towards a more Mediterranean state, before gradual cooling, and greenhouse-induced warming could delay the next full-glacial episode until beyond 170,000 years after present (BIOCLIM, 2003). Over the next five thousand years, sea-levels around the British Isles are likely to rise to about 10 to 20 m above the present-day position and be maintained at these levels until beyond 100,000 years after present (Thorne and Kane, 2006). The NDA RWMD will continue to review the science associated with long-term climate and sea-level projections and will revisit the supporting modelling once a potential site has become available.

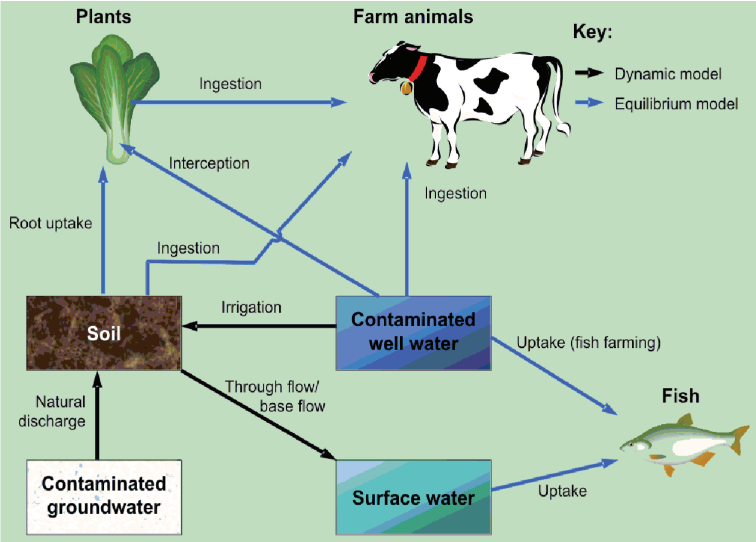

FIG. 2. Contaminant transport processes considered for release to a temperate terrestrial biosphere via the groundwater pathway.

A GDF for intermediate-level radioactive waste (and low-level radioactive waste not suitable for near-surface disposal) has the potential to generate substantial quantities of hydrogen, methane and carbon dioxide gas. These may reach the soil zone labelled with ^{14}C (the half life of tritium is sufficiently short that it will have decayed before it reaches the biosphere). The timescales of relevance to the transport of gas from the GDF to the surface are shorter than those of relevance to the groundwater pathway (this depends strongly on the specific design of the facility and on the geology in which it is sited). Carbon-14 transfers and subsequent doses to PEGs from foodchain pathways dominate those by the inhalation pathway. As carbon is a major constituent of many environmental media and all biota, it is governed by a wide range of biochemical and biogeochemical processes. Assessment of the gas pathway is therefore supported by detailed models for the behaviour of ^{14}C in the soil zone and its uptake by plants.

International engagement on the biosphere

The approach NDA RWMD has adopted to representing the biosphere in post-closure assessments has been developed over more than 20 years. International collaboration with other waste management organizations towards common goals and sharing existing knowledge has enabled NDA RWMD to provide key inputs to international recommendations relating to biosphere assessment. In providing such inputs we recognize that the environmental and regulatory contexts differ between the UK and other countries with programmes in this area, such as France, Finland and Sweden.

Particular collaborations have included:

(1) The International Atomic Energy Agency (IAEA) BIOMASS project (International Atomic Energy Agency, 2003), which recommended an overall biosphere assessment methodology.

(2) The collaborative European Union (EU) funded BIOCLIM project (BIOCLIM, 2004), which has established an international consensus regarding the interpretation and representation of long-term climate change within biosphere assessments.

(3) The on-going collaborative BIOPROTA project (Smith *et al.*, 2012), which draws together international experience regarding key pathways and contaminants in biosphere assessments and maintains close contacts with other waste management organizations with an interest in biosphere assessment issues.

Also noted are the EU funded FASSET, EPIC, ERICA and PROTECT projects (see http://wiki.ceh.ac.uk/display/rpemain/Radiological+Environmental+Protection), which are leading the

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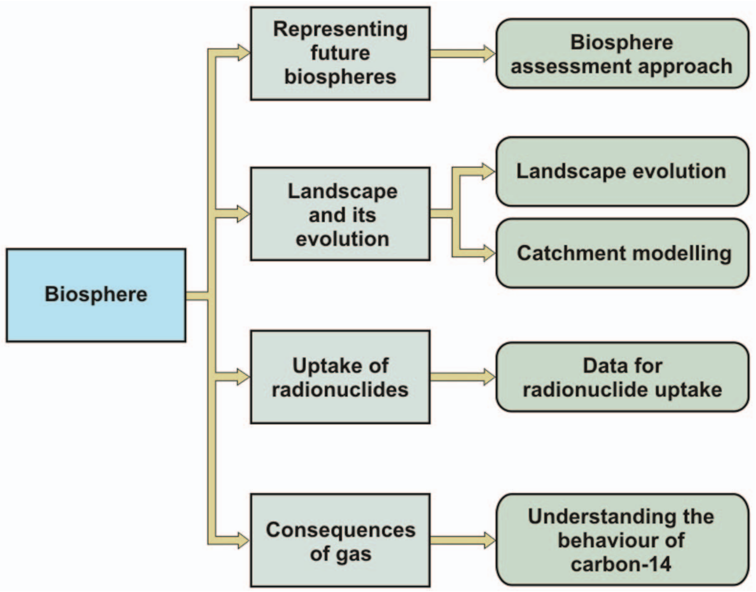

FIG. 3. Structure of the NDA RWMD biosphere research and development programme.

work towards an agreed approach for assessing potential impacts on environmental/non-human biota end points and will inform forthcoming recommendations of the International Commission on Radiological Protection (ICRP) in this area.

Biosphere research needs for the current phase

Figure 3 shows the structure of the planned future research and development programme to address currently identified gaps in our knowledge. The topics are discussed further below.

Representing future biospheres

The NDA RWMD has recently reviewed the approach it has adopted to representing the biosphere (Walke *et al.*, 2011). The results of the review will produce an update to the current biosphere assessment model and will enable new sources of information to be included (e.g. International Atomic Energy Agency, 2009, 2010) along with updated guidance on the representation of PEGs (National Dose Assessment Working Group, 2009). The NDA RWMD will also review its assessment methodology for the treatment of chemotoxic species and representation of non-human biota in the light of developing recommendations.

Uptake of ^{14}C

The NDA RWMD has commissioned research into the behaviour of ^{14}C labelled gases, with an emphasis on metabolism in the soil zone, release from the soil surface and uptake by plants. This work involves some experimental laboratory studies. It is recognized that realistic parameter values for modelling will have to be obtained under appropriate field conditions, so field experiments are also being undertaken using ^{13}C as a non-radioactive surrogate for ^{14}C.

Understanding the effects of gas

To complement laboratory and field studies on the behaviour of ^{14}C in the biosphere described above, detailed, process-based models are being developed to provide an understanding of the behaviour of ^{14}C labelled gases in the soil-atmosphere-plant system. Such models will be used to inform the top level models used in the assessment studies.

Data for radionuclide uptake

The representation of key contaminants in the biosphere is being reviewed through a series of detailed reports. A report on ^{36}Cl, ^{99}Tc and ^{129}I is available (Thorne and Limer, 2009), together with reports on ^{14}C (Limer and Thorne, 2011), ^{79}Se (Limer and Thorne, 2010) and the uranium decay

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series (Mitchell and Thorne, 2011). Information on an international ^{14}C model intercomparison is provided in Limer *et al*. (2011*a*), and results are available from international workshops on the behaviour of ^{226}Ra (Smith *et al*., 2010) and the ^{238}U decay series (Limer *et al*., 2011*b*). In addition to studies relating to key individual contaminants, key inputs to the biosphere models include collations of international radioecological data and these data will be taken into account when the biosphere models are updated.

Catchment modelling

The degree of mixing between potentially contaminated deeper groundwater and more recent meteoric groundwater in the shallow groundwater system, and the nature and distribution of its release to the surface is a key area of uncertainty in biosphere assessments. This interface between the geosphere and biosphere (Fig. 1) depends strongly on the geological environment. The capabilities of physically based, catchment-scale hydrological models such as *MIKE SHE* (Hughes and Liu, 2008) and *SHETRAN* (Ewen *et al*., 2000) are being reviewed with respect to supporting future site-specific assessment studies (e.g. Towler and Thorne, 2008; Towler *et al*., 2011).

Landscape evolution

The BIOCLIM project (BIOCLIM, 2003, 2004) provides the basis for the climate change scenarios that are considered in the biosphere assessment studies. The science that underpins climate change modelling and the associated modelling capabilities continues to develop. The importance of long-term climate change and its impact on landscape evolution will differ depending on the site being considered (e.g. the potential significance of future sea-level change). Therefore, it is planned to update the analysis relating to long-term climate change once the site selection process has progressed to considering potential sites. Developments in site characterization will continue to be monitored, in so far as they support the biosphere programme.

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