



Representation of estuarine, coastal and marine biosphere systems within post-closure performance assessments supporting geological disposal of higher activity radioactive wastes in the UK

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ABSTRACT

Radioactive Waste Management Limited (RWM) is tasked with implementing geological disposal of the United Kingdom's (UK) higher activity radioactive wastes. This paper describes how RWM's biosphere modelling capability has been extended from a solely terrestrial model to allow potential contaminant releases to estuarine, coastal and marine systems around the UK to be represented. The new models aim to strike a balance between being as simple as can be justified, erring on the side of conservative estimates of potential doses, while also representing the features and processes required to reflect and distinguish UK coastal systems. Sediment dynamics (including meandering of estuaries and sediment accumulation) are explicitly represented in a simplified form that captures the accumulation and remobilization of radionuclides. Long-term transitions between biosphere systems (such as from a salt marsh to a terrestrial system) are outside the scope of the study. The models and supporting data draw on information about the UK that is representative of present-day conditions and represent potential exposures arising from both occupational and recreational habits.

Generic calculations demonstrate that potential doses to humans arising from releases to estuarine, coastal and marine systems are typically more than two orders of magnitude lower than those for equivalent releases to terrestrial systems via well water and groundwater discharge to soil. The extended capability (i) ensures that RWM is able to undertake assessments for potential coastal site contexts, if and when required, and (ii) provides RWM with quantitative evidence to support the principal focus on terrestrial releases (particularly for more generic assessments).

KEYWORDS: radioactive waste, biosphere, estuary, coastal, marine, dose assessment.

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Introduction

RADIOACTIVE Waste Management Limited (RWM) is tasked with implementing geological disposal of the United Kingdom's (UK) higher activity radioactive wastes. Generic safety cases supporting geological disposal in the UK have focused on potential doses that might arise to humans if radionuclides from a geological disposal facility (GDF) enter the terrestrial biosphere system (NDA, 2010). Focus on terrestrial and freshwater systems was justified on the basis of the greater dilution that generally occurs with releases to estuarine and marine systems. This paper describes a study (Walke *et al.*, 2013a) that sought to (i) extend RWM's biosphere modelling capability to allow potential releases to estuarine, coastal and marine systems around the UK to be represented, and (ii) explicitly compare potential impacts arising from releases to terrestrial/freshwater and estuarine/marine systems.

The uncertainties inherent in making projections of hypothetical situations into the long-term future (extending to tens or even hundreds of thousands of years) mean that the assessment results cannot be considered to represent a prediction of the future. The biosphere calculations are instead intended to assess the range of potential exposures that might occur under different assumptions about future scenarios. The role of radiological assessments within this context is therefore to act as a means for evaluating the potential significance of calculated fluxes of radionuclides to the biosphere.

The assumptions required to support a biosphere assessment aim to be plausible, internally consistent and, in general, tend to err on the side of caution and conservative estimates of potential doses. This balance is achieved by generally seeking to adopt realistic values and ranges for parameters that contribute towards the calculation of contaminant concentrations in the biosphere, while adopting more cautious assumptions relating to the location and behaviour of potentially exposed groups (PEGs) among the population that is assumed to make use of environmental resources. This approach is consistent with international recommendations (see Section 5.1 of ICRP, 2013) and aims to ensure that potential exposures are not underestimated, but at the same time avoids excessive pessimism.

The work described in this paper focuses on radionuclide discharges to the biosphere and potential impacts on humans, however, the same

modelling approach can be used as a basis for assessing non-radiological contaminants and as a basis for evaluating potential radiation doses to biota other than humans.

Potential radionuclide releases to estuarine, coastal and marine systems

The modelling reflects potential discharges of groundwater contaminated with radionuclides from a GDF to estuarine, coastal and/or marine biosphere systems. Discharges may also reach these systems following releases to terrestrial and/or freshwater systems. Models are needed to represent radionuclide behaviour and potential exposure within each of these systems, as well as potential exchanges and transfers of contaminants between them.

With leaching/release of radionuclides to surface waters and erosion of soils and sediments retaining less mobile radionuclides, the majority of radioactivity released to terrestrial systems will ultimately reach the coast provided that the timescale for radioactive decay is significantly greater than the hold-up time in the terrestrial and freshwater system. As a general rule, the hold-up time within terrestrial biosphere systems can be expected to be relatively short by comparison with both the timescale since disposal and the radioactive decay times of any radionuclides that reach the terrestrial system in significant quantities. It is therefore reasonably cautious to assume that all the activity that enters the terrestrial system will end up discharging to estuaries and/or through the coast/seabed. For discharges to terrestrial/freshwater systems, the double-counting that occurs when also applying the same release direct to the decoupled estuarine and/or coastal system has to be acknowledged.

Estuarine and coastal environments tend to be highly labile, being affected by sea level and changes in sediment supply. In particular, estuaries tend to be net sediment deposition systems, with fluviially transported sediments interacting with incoming tidal waters to give rise to deposition either within the estuary or in a submarine delta beyond its mouth. Thus, estuaries are fundamentally transient structures with characteristic life-times measured in centuries or, at most, a few millennia (Woodroffe, 2003).

Radionuclides are not expected to be retained on very long timescales in the more labile estuarine and coastal parts of the system. Long-term

environmental change within these systems need not be explicitly represented because their relatively labile nature means that they are unlikely to give rise to accumulation beyond what would be predicted by a non-evolving representation. The models therefore represent snapshots of possible configurations of estuarine, coastal and marine geometry.

Water exchanges and sediment dynamics are key factors in determining the behaviour of contaminants in estuarine, coastal and marine systems. Estuarine and marine sediments are represented as multiple one dimensional columns that are discretized to represent the dynamics involved (see Fig. 1). Net sedimentation is represented with a loss from the system (illustrated as a transfer to a 'sediment sink' in Fig. 1).

Estuarine systems

Radionuclides can enter estuaries in river flow, including those sorbed to suspended sediment, or as a consequence of surface and sub-surface runoff from terrestrial areas. Radionuclides entering the estuary by these routes are taken initially to be assigned to the water column in the estuary (which includes the sediment suspended within it). Radionuclides can also enter the estuary in upwelling contaminated groundwater and as the bedrock in estuaries is generally overlain by unconsolidated sediments, the release of radionuclides via this route will generally be through

those sediments. However, as has already been noted, estuaries typically exhibit net sedimentation and this would generally occur at a faster rate than radionuclides would disperse upward in the sediment in a purely diffusive system. Therefore, it is important to include the upward groundwater velocity in the model, so that the advective transport of radionuclides occurs in and through the bottom sediments. There may also be some areas of the estuary where the bedrock is exposed (e.g. at the bottom of the main tidal flow channel or in peripheral areas where sediments have recently been removed during storms). Therefore, the model allows for a fraction of radionuclides entering the estuary in upwelling groundwater to be routed directly to the water column (see Fig. 2).

Well-mixed, tide-dominated estuaries are of greatest relevance in the UK and are typically funnel shaped, with wide entrances tapering upstream. Where channel banks are unconsolidated or poorly consolidated, as is often the case in the UK, there is a tendency for a negative exponential decrease in width with distance upstream. Sandy shoals, elongated parallel to the flow, are often prominent features within the mouth. These estuaries are well mixed as a result of strong bi-directional tidal currents. Rapid flows resuspend and transport sediments.

Three zones with distinct channel morphology can typically be recognized within estuaries. These comprise an upstream river-dominated zone, a central mixed-energy zone and a seaward marine-dominated zone (Woodroffe, 2003); these zones are

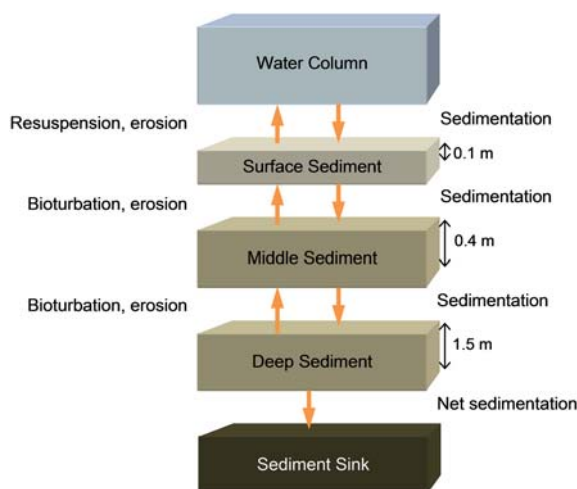


FIG. 1. Vertical discretization used to represent estuarine and marine sediments. The fixed depths of the sediment compartments are based on judgement as to typical depths for fast, moderate and slow turnover by bioturbation.

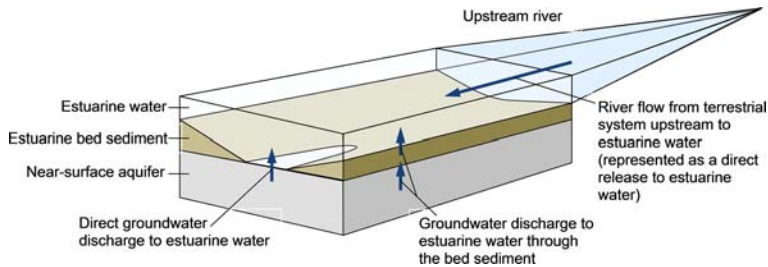


FIG. 2. Components of the estuary model, along with potential contaminant release pathways.

explicitly represented in the model. The upstream zone is often relatively straight, with net seaward sediment movement by fluvial processes. The central zone is a zone of sediment convergence influenced by both river and marine processes, often with a highly sinuous channel. The seaward zone is relatively straight, its banks are funnel shaped, and sediment moves in a net landward direction. Though this simplified representation inevitably results in significant spatial averaging of estimated activity concentrations, such averaging is appropriate for calculation of dose since habits data indicates that marine and estuarine foodstuffs are gathered and consumed from a relatively wide spatial area (EA *et al.*, 2013, and supporting references).

Although the geometry of the estuary is fixed, sedimentation and resuspension are explicitly modelled and are parameterized to include consideration of channel meander. Net sedimentation without modifying the size of the tidal prism implies a slight inconsistency in model formulation, however, the implications of this inconsistency are considered to be minor. An analogy can be drawn with long-term assessments within surface water catchments where radionuclide movement

due to erosion is represented, but changes in hillslope geometry due to denudation are not represented (e.g. Walke *et al.*, 2013b).

Coastal systems

From a modelling perspective, the coastal system is taken to be the inter-tidal area of beach and/or foreshore rock. Potential radionuclide releases to these systems are represented, along with potential contamination of those environments from the marine system. Groundwater may emerge as springs or seeps (see Fig. 3). These could be on the cliff face above or below the level of the surface of the storm beach or on the foreshore. Springs or seeps at the cliff face may result in streams of fresh water running over the surface of the beach. On rocky foreshores upwelling groundwater may contribute to the water in rock pools, though a major component of such pools will generally be sea water that is retained as the tide falls. Thus, radionuclide concentrations and salinities in rock pools may vary substantially over each tidal cycle. This may be of particular importance in evaluating radiation exposures of non-human biota and their

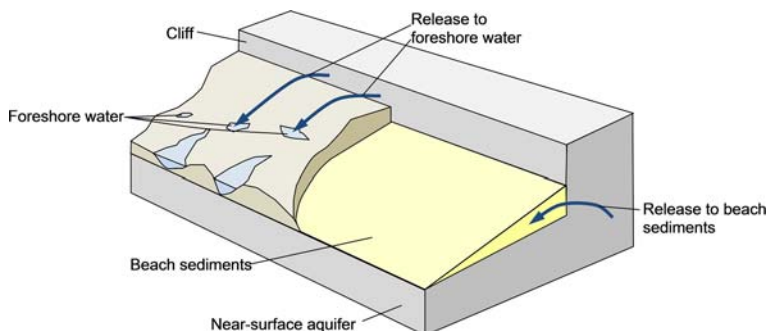


FIG. 3. Components of the model for the beach and foreshore, along with potential contaminant release pathways.

ecological significance, but is not represented in the model, which does not extend to wildlife dose assessment, as described previously.

Radionuclide interactions with the coarse (gravel to boulder) material of storm beaches will be limited because of the small surface to volume ratio of this material and the ease with which water percolates through it. Although there will be a greater degree of interaction with sand-sized material, sorption will generally be less than it would be on silt or clay materials because of its lower specific surface area and the lower sorption capacity of sand in comparison to silt and clay minerals. Therefore, the degree of hold up of radionuclides in sandy beaches and rocky foreshores is likely to be limited. However, as with the estuary, it is appropriate to represent transport through the sediments taking into account the advective velocity of the discharging groundwater.

Beach and foreshore sediments are reworked regularly, often with substantial differences in the beach profile between summer and winter. Thus, relatively rapid exchanges of sediment between the coastal strip and the near-shore deposited sediments will occur. In addition, there will be a rapid exchange of water between that contained in the beach and foreshore (either as porewater within the beach materials, or in rock pools, etc.) and that in the near-shore water column.

The turnover of beach sediments, which is relatively rapid in comparison to the timescales of groundwater releases and radiological assessment, means that they can be adequately represented with a single well-mixed compartment. Radionuclide concentrations in the foreshore water are calculated as an average of the concentration in discharging groundwater and the concentration in the local marine water, based on turnover with each tide.

Marine systems

The marine system includes exchanges with both the estuarine and coastal systems, as well as potential direct discharges of contaminated groundwater; the latter is illustrated in Fig. 4.

Parameterization

The models are parameterized with ranges appropriate to the UK, drawing on studies including Dewar *et al.* (2011) as well as other radiological assessment frameworks, including Smith and Simmonds (2009). Dewar *et al.* (2011) used data for the UK to illustrate the relationship between compartment volumes and exchange rates (see Fig. 5), both of which are parameterized in the models summarized in this paper.

Potential exposures

Consideration is given to potential exposures that may arise through both occupational and recreational habits. Occupational and recreational groups are considered for the estuarine environment, to reflect, for example, activities such as bait digging, grazing animals on the salt marsh and fishing. A single set of occupational and recreational groups is also considered for the marine and coastal systems, reflecting, for example, commercial inshore fishing along with recreational use of a beach and foreshore, including swimming and rock-pooling.

Given the long timescales relevant to post-closure radiological assessments associated with geological disposal, equilibrium assumptions are used to represent uptake by plants and animals. Foodstuffs represented in the models include meat

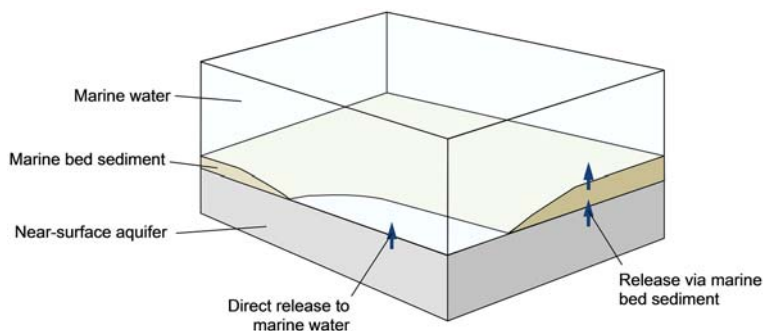


FIG. 4. Components of the model for the marine system, along with potential contaminant release pathways.

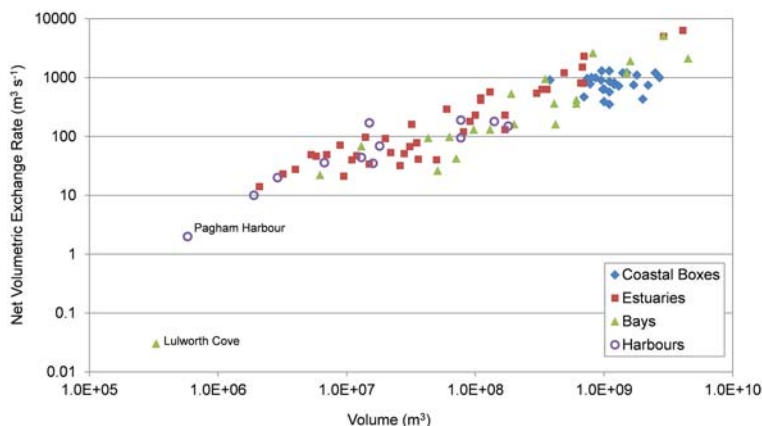
FIG. 5. Net exchange rate vs. volume, based on data in Dewar *et al.* (2011).

TABLE 1. Key radionuclides for intermediate-level wastes, high-level wastes and spent fuel, based on Limer and Thorne (2011).

^{14}C	$^{93\text{m}}\text{Nb}$	^{126}Sn	^{210}Pb	^{232}Th	^{238}U	^{241}Am
^{36}Cl	^{94}Nb	^{129}I	^{226}Ra	^{231}Pa	^{237}Np	$^{242\text{m}}\text{Am}$
^{59}Ni	^{93}Mo	^{135}Cs	^{228}Ra	^{232}U	^{238}Pu	^{243}Am
^{63}Ni	^{99}Tc	^{137}Cs	^{227}Ac	^{233}U	^{239}Pu	^{243}Cm
^{79}Se	^{107}Pd	^{151}Sm	^{228}Th	^{234}U	^{240}Pu	^{244}Cm
^{90}Sr	$^{108\text{m}}\text{Ag}$	^{152}Eu	^{229}Th	^{235}U	^{241}Pu	^{245}Cm
^{93}Zr	$^{121\text{m}}\text{Sn}$	$^{166\text{m}}\text{Ho}$	^{230}Th	^{236}U	^{242}Pu	^{246}Cm

and milk from grazing on salt marsh; fish, crustaceans and molluscs from the sea, estuary and foreshore. Although uncommon, ingestion of seaweed and plants foraged from the coastal area are also included. Calculated concentrations on the coastal plants include contamination arising from sea-to-land transfer of spray and spume.

Modelling approach

A compartment modelling approach is adopted, whereby the estuarine, coastal and marine systems are discretized into distinct compartments/cells within which it is appropriate to consider contaminants to be homogeneously distributed on the multi-annual timescales for transport that are relevant to post-closure assessments. Distinct models for the estuarine, coastal and marine systems are integrated with the existing model for terrestrial systems in GoldSim (2014), consistent with other aspects of RWM's post-closure assessments.

Radionuclide fluxes into the biosphere can be applied to the model, which then calculates associated annual effective doses¹. Alternatively, the model can be used to calculate equilibrium dose conversion factors that convert radionuclide fluxes from the geosphere (Bq/y) into effective dose rates (Sv/y), including the contribution from radioactive progeny that are produced after release to the biosphere. The model calculates dose conversion factors for 49 radionuclides that have been identified as meriting consideration in biosphere assessments for the UK geological disposal programme (see Table 1, based on Limer and

¹The effective dose is the sum over radiation doses to individual tissues and organs of the body weighted by a measure of the biological effectiveness of the particular type of radiation in inducing adverse health effects and by the relative radiosensitivity of the individual tissues and organs.

Thorne, 2011). Radionuclides with half-lives shorter than about 100 days are taken to be present in secular equilibrium with their parents and their contribution is included in the dose coefficients for ingestion, inhalation and external irradiation used in the modelling.

Results

Reference calculations have been undertaken for radionuclide releases to the estuary bed sediment, which are shown to typically result in the highest dose conversion factors and which also result in potential exposure of the marine group arising from contamination of the marine and beach/foreshore systems after the radionuclides have left the estuary.

The behaviour of radionuclides released into the estuary is dependent on their degree of retention on sediments. Where there are sufficient data, the model distinguishes between the degree of sorption on oxic and anoxic sediments. Figure 6 compares the calculated concentrations of radionuclides in the water compartments with differing degrees of sorption for a unit release rate (1 Bq/y) to the upstream estuary (^{14}C being represented with zero sorption and ^{126}Sn with strong sorption onto sediments). The figure shows the effect of increasing dilution, as the radionuclides get further away from the source, and the effect of increasing sorption on the degree of retention. The figure also shows that the concentration in foreshore water (e.g. rock pools) matches that in the local marine water. This is because the potential diluting effect of uncontaminated groundwater discharges to the foreshore water is conservatively ignored in this case.

Evaluation of dose conversion factors arising from releases to the estuary shows that the

occupational estuarine group receives the highest calculated doses, reflecting both the relatively long period of time that they are taken to spend in the contaminated region (2000 hours per year, equivalent to more than five hours per day every day of the year) as well as the wide range of exposure pathways (including meat and milk from animals grazing on the salt marsh).

Groundwater releases direct to the beach and foreshore water result in dose conversion factors that are comparable with those associated with a release to the estuary bed sediment. On average, the dose conversion factors for releases to the coastal system are lower, although they are higher for about 40% of the radionuclides modelled. The greatest contribution for those that have the largest increase over releases to the estuary bed sediment is generally due to external irradiation because the unit release rate to the coastal system is accompanied by a smaller volume of groundwater discharge to a single sediment layer on the beach, resulting in higher maintained concentrations in the beach.

Direct groundwater releases to the local marine bed sediments result in dose conversion factors that are again comparable with those associated with a release to the estuary bed sediment. On average, the dose conversion factors for releases to the local marine system are lower, although they are higher for about 25% of the radionuclides modelled. In most cases, the greatest contribution (for those that are higher than for releases to the estuarine system) is again due to external irradiation from the beach, which exchanges sediment relatively rapidly with the local marine bed sediment that receives the contaminated groundwater discharge.

For radionuclide releases to reference-sized estuarine, coastal and marine systems, the maximum dose conversion factors are shown to

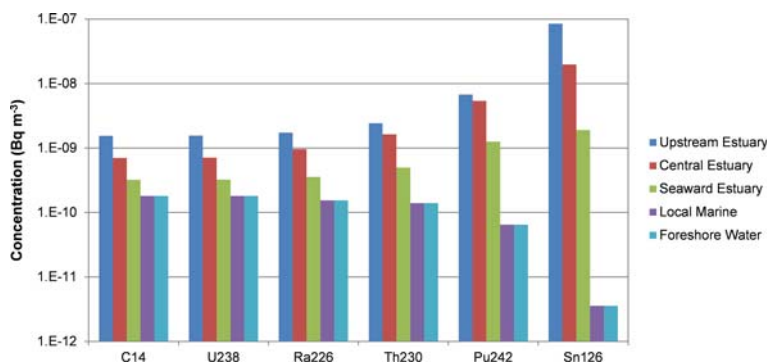


FIG. 6. Concentrations in water compartments for a unit release rate to the estuary.

be typically more than two orders of magnitude lower than those that are calculated for a terrestrial/freshwater system contaminated via both groundwater discharge and use of contaminated well water (described in Walke *et al.*, 2013*b*). However, the results are sensitive to the sizes of the estuarine, coastal and marine systems, because smaller systems result in less dilution. Dose conversion factors calculated for releases to small estuarine, coastal and marine systems increase so that they can be within only a factor of about three of those for releases to a terrestrial system. Indeed, calculated concentrations in small systems can exceed those calculated for releases to a terrestrial system; the calculated doses are lower only because of the more limited range of potential exposure pathways.

Conclusions

Generic models for potential radionuclide releases in groundwater from a GDF to estuarine, coastal and marine environments in the UK have been developed. The resulting calculations demonstrate that potential doses to humans arising from releases to estuarine, coastal and marine systems are typically more than two orders of magnitude lower than those for equivalent releases to terrestrial systems via well water and groundwater discharge to soil. The lower dose conversion factors are a result of the increased dilution that is encountered in these systems along with the more limited range and extent of potential exposure pathways.

The results from the models for estuarine, coastal and marine systems are sensitive to the size of the environments being represented, with dose conversion factors being higher for releases to smaller systems, reflecting a lower degree of dilution. The models represent a first iteration of generic biosphere assessment models for these systems in the UK and merit further consideration, notably to explore sensitivities to parameters other than the assumed size of the systems and to review the suitability of the models for representing environmental and climate changes that are projected to occur in the UK over the timescales relevant to post-closure assessments.

Acknowledgements

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References

- Dewar, A., Jenkinson, S. and Smedley, C. (2011) *Parameter Values used in Coastal Dispersion Modelling for Radiological Assessments*. Environment Agency report SC060080/R3, February 2011.
- EA, FSA, NIEA and SEPA (2013) *Radioactivity in Food and the Environment, 2012*. Report compiled by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) on behalf of the Environment Agency, Food Standards Agency, Northern Ireland Environment Agency and the Scottish Environment Protection Agency, RIFE 18, October 2013.
- GoldSim (2014) Monte Carlo Simulation Software. www.goldsim.com/
- ICRP (2013) *Radiological Protection in Geological Disposal of Long-lived Solid Radioactive Waste*. Annals of the ICRP, 42(3).
- Limer, L.M.C. and Thorne, M.C. (2011) *NDA RWMD Biosphere Assessment Studies FY2010-2011: Radiological Screening*. Quintessa Limited report to the Nuclear Decommissioning Authority Radioactive Waste Management Directorate QRS-1378ZM-2, Version 1.0, February 2011.
- NDA (2010) *Geological Disposal: Biosphere Status Report*. Nuclear Decommissioning Authority report NDA/RWMD/036, December 2010.
- Smith, J.G. and Simmonds, J.R. (Editors) (2009) *The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment used in PC CREAM 08*. Report of the Radiation Protection Division of the Health Protection Agency, HPA-RPD-058, October 2009.
- Walke, R.C., Thorne, M.C. and Smith, J.T. (2013*a*) *RWMD Biosphere Assessment Model: Marine Component*. AMEC report to NDA RWMD 18025/TR/001, Issue 2.0.
- Walke, R.C., Thorne, M.C. and Limer, L.M.C. (2013*b*) *RWMD Biosphere Assessment Model: Terrestrial Component*. AMEC report to NDA RWMD 18025/TR/002, Issue 2.0.
- Woodroffe, C.D. (2003) *Coasts: Form, Process and Evolution*. Cambridge University Press, Cambridge, UK.