Journal of Environmental Management 171 (2016) 195–203

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Derivation of risk indices and analysis of variablility for the management of incidents involving the transport of nuclear materials in the Northern Seas

J. Brown [b, c], A. Hosseini [b, c], M. Karcher [a, d], F. Kauker [a, d], M. Dowdall [b, *], R. Schnur [a], P. Strand [b, c]

[a] *O.A.Sys – Ocean Atmosphere Systems GmbH, Tewessteg 420249 Hamburg, Germany*
[b] *Norwegian Radiation Protection Authority, PO Box 55, N-1332 Østerås, Norway*
[c] *CERAD, Ås, Norway*
[d] *Alfred Wegener Institute for Polar and Marine Research, 27515 Bremerhaven, Germany*

A R T I C L E   I N F O

Article history:
Received 12 November 2015
Received in revised form
22 January 2016
Accepted 8 February 2016
Available online 16 February 2016

Keywords:
Radioactivity
Transport
Management
Assessment
Variability
Risk

A B S T R A C T

The transport of nuclear or radioactive materials and the presence of nuclear powered vessels pose risks to the Northern Seas in terms of potential impacts to man and environment as well socio-economic impacts. Management of incidents involving actual or potential releases to the marine environment are potentially difficult due to the complexity of the environment into which the release may occur and difficulties in quantifying risk to both man and environment. In order to address this, a state of the art oceanographic model was used to characterize the underlying variability for a specific radionuclide release scenario. The resultant probabilistic data were used as inputs to transfer and dose models providing an indication of potential impacts for man and environment This characterization was then employed to facilitate a rapid means of quantifying risk to man and the environment that included and addressed this variability. The radionuclide specific risk indices derived can be applied by simply multiplying the reported values by the magnitude of the source term and thereafter summing over all radionuclides to provide an indication of total risk.

1. Introduction

While land-based nuclear facilities such as the reprocessing plants of western Europe have been and will probably remain the most significant contributors of contaminant radionuclides to the Northern Seas (AMAP, 2010), seagoing vessels powered by or transporting nuclear materials also pose risks. Nuclear-powered vessels of a number of nations have operated in northern waters for many decades. Civilian transport of nuclear fuel cycle materials – ranging from low level "frontend" materials to high level "back-end" wastes – has been carried out through these waters for many years (Gaffney, 2011). Although the Northern Seas in which such traffic is found is a valuable fishery, the productive waters around the Lofoten archipelago, located between the 68th and 69th parallels, are widely considered as an especially rich fisheries resource (Olsen et al., 2010). The area plays an especially important role in the life cycles of Northeast Arctic cod (*Gadus morhua*) and Norwegian spring-spawning herring (*Clupea harengus* L.), which comprise the largest populations (IMR, 2013). Although less important economically, other species for which the area is important include Northeast Arctic haddock (*Melanogrammus aeglefinus*), Northeast Arctic Pollock (*Pollachius virens*), deepwater redfish (*Sebastes mentella*), tusk (*Brosme brosme*) and ling (*Molva molva*).

The consumer confidence of the general public has historically been acutely sensitive to radioactive contamination of the marine environment and there is no evidence of this changing in coming years. Incidents over recent decades have provided evidence of this sensitivity which extends to even rumours concerning potential contamination and can result in socio-economic consequences out-of-proportion to risks posed by actual or potential contaminant levels. The focus of recent specific attention has been the risks posed by the transport of nuclear materials and nuclear powered vessels. Concerning the latter, the aftermath of the "Komsomolets"

* Corresponding author.
E-mail address: mark.dowdall@nrpa.no (M. Dowdall).

http://dx.doi.org/10.1016/j.jenvman.2016.02.012
0301-4797/© 2016 Published by Elsevier Ltd.

submarine accident in the Norwegian Sea in 1989 (see Høibråten et al., 1997) and the loss of the "Kursk" in 2000 in the Barents Sea (see Amundsen et al., 2002) effectively demonstrated heightened public awareness regarding potential, yet ultimately unactualised contamination. Although there has never been a significant release of radioactive materials from a civilian vessel transporting nuclear waste or spent fuel (IAEA, 2001), the operation of such vessels has been a source of public unease. This unease has recently been in relation to the transport of nuclear materials to and from European reprocessing facilities and Global Threat Reduction Initiative (GTRI) shipments. Given the nature of such transports, detailed information is sparse even though a number of the shipments have received intense media and national authority attention in some countries. The MV "Puma" transported spent nuclear fuel from a research reactor in Belgrade to the Russian port of Murmansk during 2010 travelling a route along the Norwegian coast. In the same year, the MCL "Trader" transported enriched uranium from Poland along the same route. Czech spent nuclear fuel was transported on the "Mikhail Dudin" to Murmansk early in 2013, again, along the coast of Norway. All these shipments were subjected to intense media and public attention in a number of countries, elevating public concern and consumer unease about the sea transport of nuclear materials to heights not seen since the closing decades of the last century.

In managing the Northern Seas with respect to potential impacts from contaminant radionuclides, risks to human health are the primary focus. Once initial concerns about the health of the public have been addressed, or where human health impacts cannot occur, emphasis is often placed on estimating environmental risk, a measure which can then be employed within management strategy options. When fulfilling the requirement to consider post-accident environmental radiation impacts, the International Commission on Radiological Protection (ICRP) argue that adopting a suitable approach to estimating environmental risk may be useful in stakeholder communication, particularly in relation to environmental conditions where risk to humans has been prevented (ICRP, 2014). This subordinate consideration of risk to the environment has, arguably, not been well addressed until recently as there are no universally agreed methods of defining risk to the environment and this constitutes a clear gap in available management options.

Regarding potential human impacts of an accident or release involving radioactive materials, one viable strategy may be critically comparing predicted seafood concentrations with current contamination levels in harvested species of fish etc. for relevant areas or against pertinent intervention limits. This is essentially the approach employed in Heldal et al. (2013) in considering the impact on the Barents and Norwegian Seas from the "Komsomolets" and "K-159" submarines following hypothetical releases and subsequent available management options. The Norwegian intervention level of 600 Bq/kg fresh weight (f.w.) for ^{137}Cs in food and a background level of 0.2 Bq/kg f.w. ^{137}Cs, were used to place model prognoses in context (Heldal et al., 2013). A more direct approach to define human risk could possibly be through comparison of human (committed effective) doses with relevant benchmarks such as a *de minimis* level. This alternative might be considered more 'direct' as the concept of dose is more directly linked to potential human health impacts through, for example, the nominal coefficient for detriment-adjusted risk (ICRP, 2007). An approach using intervention levels has a somewhat less tangible link to risk as, in many instances, other considerations such as political, societal and economical perspectives are introduced. Methodological components facilitating estimation of human and environmental risk are intrinsic requirements for robust assessments of the impact of radionuclide releases as part of a management strategy. It is well established that complex environmental systems can be highly variable – both temporally and spatially - and some means of quantifying this variability needs to be available. Predictions cannot be made months in advance because the weather conditions leading to the dispersion of contamination when an accident might occur, and in the period following the accident, are essentially unknown, thereby hampering the management strategy.

Currently, the best that can be hoped for is development of a retrospective analysis, covering an acceptably long period of time (perhaps several decades) wherein the probability of capturing extreme or unusual periods of contaminant dispersal is high. This may facilitate the characterisation of the long-term variability of the system to a reasonable degree. The marine dispersion of radionuclides from a source is affected by the variability of oceanic currents with respect to flow speed, vertical and horizontal mixing intensity and the width and depth of the currents. This current variability can arise due to local or small-scale forced processes and unforced processes (internal variability of the sea-ice-ocean system). In addition large-scale flow pattern changes, often linked to specific atmospheric forcing patterns, have the potential to significantly alter the pathways of dispersion.

The objective of this study was to attempt to characterize the underlying variability, based on the aspects outlined above, for a given radionuclide release scenario. This characterization would then be used to facilitate a rapid means of quantifying human and environmental risk that includes this variability and which could form part of a management plan after a release of radioactivity to the Northern Seas.

2. Study methodology

The 2006 Management Plan for the Marine Environment of the Barents Sea–Lofoten Area (see Royal Norwegian Ministry of the Environment, 2006) included identification of especially valuable and vulnerable areas within the geographic area covered by the plan. These sub-areas are those that, on the basis of scientific evaluations, were evaluated as being vital to the biodiversity and biological productivity of the Barents Sea–Lofoten area, based upon a number of factors such as the nutrient status of the seawater, phytoplankton production or being spawning grounds or a migration route. The presence of colonies, breeding areas or other concentrations of marine mammals such as grey and common seals, common porpoises, killer whales, sponge communities and coral reef complexes were also sufficient to denote an area as especially valuable or vulnerable.

Of especial interest to this study was the region extending from the Lofoten Islands to the Tromsøflaket, the Tromsøflaket bank area, and the Eggakanten area (see Fig. 1). The Lofoten Islands-Tromsøflaket area was focussed upon due to its being a valuable and vulnerable area (as described previously) and it's also being one of Norway's most commercially important fisheries. The data generated in relation to this area formed the basis for the development of the probability density functions (pdfs) used in subsequent risk calculations as described in this work. The selection of the hypothetical release point for radionuclides was based on considered evaluation and no measure of the probability of a release occurring at this particular point was or should be assigned to it. The main criterion used in selection was that the point of release would be located 'up-stream' of environmentally vulnerable and important commercial fishing areas along the coast. The selection of a release point in the Skagerrak was thus suitable within the overall context of the work in that a large proportion of the radionuclides "released" could reasonably be expected to be transported via the Norwegian Coastal Current (see Fig. 2). This route would then carry contamination through important fish