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A sensitivity analysis of a radiological assessment model for Arctic waters

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Abstract A box model has been used to calculate the environmental dispersion of radionuclides in Arctic waters and the subsequent exposure of man from a range of exposure pathways. A sensitivity analysis has been carried out to identify components of the model that are potentially important contributors to the predictive accuracy. The components investigated include features associated with water transport and mixing, particle scavenging, water-sediment interaction and biological uptake.

Introduction

Information on disposal of radioactive waste in the shallow waters of the Arctic Seas by the former Soviet Union became available to the international community from official Russian sources in 1993 in the White Book [1]. Since then several initiatives have been taken to assess the potential impact to man and the environment from this waste. Dumping has taken place in the Barents Sea west of Novaya Zemlya and in the Kara Sea east of Novaya Zemlya during the period 1960-1991.

The countries bordering the Arctic Seas are particularly concerned about the possible contamination of marine produce from these waters. Norway and the Russian Federation have entered into close co-operation to investigate the present levels of artificial radionuclides in the environment near the sites where solid reactor waste and spent nuclear fuel have been dumped in the Kara Sea. The International Atomic Energy Agency (IAEA) launched in 1993 the "International Arctic Seas Assessment Project (IASAP)" which is planned to last for four years. The programme is organised by IAEA in co-operation with Norway and Russia. Several projects supported by the European Union include supplementary investigations of the potential impact. The present paper describes a parameter sensitivity analysis of a radiological assessment model for the Arctic waters for the purpose of identifying important contributions to the predictive accuracy of the model.

Materials and methods

Model description

The marine dispersion model covers the Arctic Ocean and the North Atlantic Ocean. Box-model analysis used to simulate the movement of radioactive material between the different boxes into which the marine environment is subdivided. This type of modelling assumes instantaneous uniform mixing within each box with rates of transfer being proportional to the inventories of material in the source boxes.

Box models have been used in connection with studies of the dispersion of discharges of radioactivity from European civil nuclear installations [2]. The present model is a combination of two models: 1) an adjusted version [3] of a regional box model used for radiological assessments in north-west European coastal areas [4]; and 2) a larger box model covering the Arctic Ocean and the North Atlantic [5]. The larger box model is derived from a world ocean General Circulation Model [6] from which the results have been used for the design of a box structure in the Arctic Ocean and surrounding waters.

The box-model analysis uses first order differential equations to describe the transfer of contaminants between the boxes. The equations are of the form:

$$\frac{dA_i}{dt} = \sum_{j=1}^{n} k_{ji} A_j - \sum_{j=1}^{n} k_{ij} A_i - k_i A_i + Q_i$$

where $k_{ii}=0$ for all i, A_i and A_j are activities (Bq) at time t in boxes i and j, k_{ij} and k_{ji} are rates of transfer (y^{-1}) between boxes i and j, k_i is an effective rate of transfer of activity (y^{-1}) from box i taking into account loss of material from the compartment without transfer to another, for example radioactive decay, Q is a continuous source of input into box i (Bq y^{-1}) and n is the number of boxes in the system.

The rates of transfer between the aquatic boxes, k_{ij} are related to the volume exchanges, R_{ij}, according to:

$$R_{ij} = k_{ij} \cdot V_i ,$$

where V_i is the volume of water represented by box i.

Figure 1 shows the regions used in the marine box model in the Arctic Ocean. Each of the water compartments contains associated suspended sediment, and the water compartments in contact with the seabed have underlying seabed sediment compartments. Details of compartment volumes, depths, suspended sediment loads, sedimentation rates and volume exchange rates may be found in [7]. The suspended sediment loads and sedimentation rates are default values from the regional model mentioned above [4].

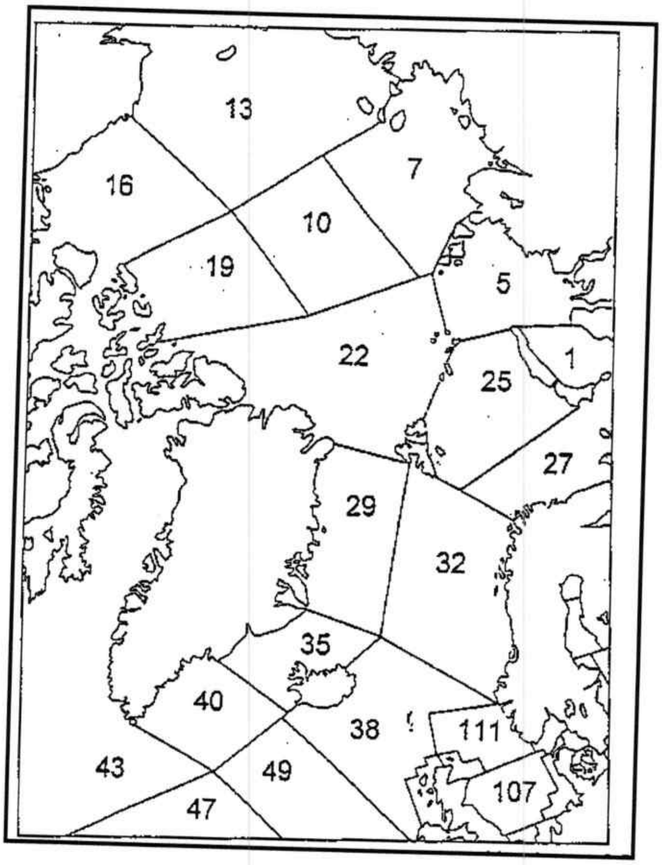


Figure 1. Regions in the Arctic Ocean covered by the model. The numbers refer to surface water boxes.

At any given time the activity in the water column is partitioned between the water phase and the suspended sediment material. The fraction of the activity (F_W) in the water column which is in solution is given by:

$$F_W = \frac{1}{1 + K_d SSL},$$

where K_d is the sediment-water distribution coefficient and SSL the suspended sediment load. Activity on suspended sediments is lost to the underlying boxes when particulates settle out. The fractional transfer from a water column (box i) to the sediments (box j) due to sedimentation is given by:

$$k_{ij} = \frac{K_d SR_i}{d_i (1 + K_d SSL_i)},$$

where d_i is the mean water depth of the water column and SR the mass sedimentation rate. Transfer between the sediment box and the water column is parameterized by diffusivity through the pore water and diffusivity due to bioturbation which gives the following transfer across the boundary:

$$\frac{dA}{dt} = (B + \omega D) S \frac{C_S - C_W}{h_B},$$

where A is the radionuclide inventory in the water column, B the bioturbation coefficient, ω the sediment porosity, D the pore water diffusion coefficient, S is the surface area of the interface, C_S the radionuclide concentration in sediment pore water, C_W the radionuclide concentration in the water column, and h_B the thickness of the bioturbated layer. Furthermore, removal of activity from the top surface sediment to lower sediment layers is taken into account by assuming that the burial rate is equal to the flux of particles which settle from the overlying waters. Radioactive decay is included in all the boxes.

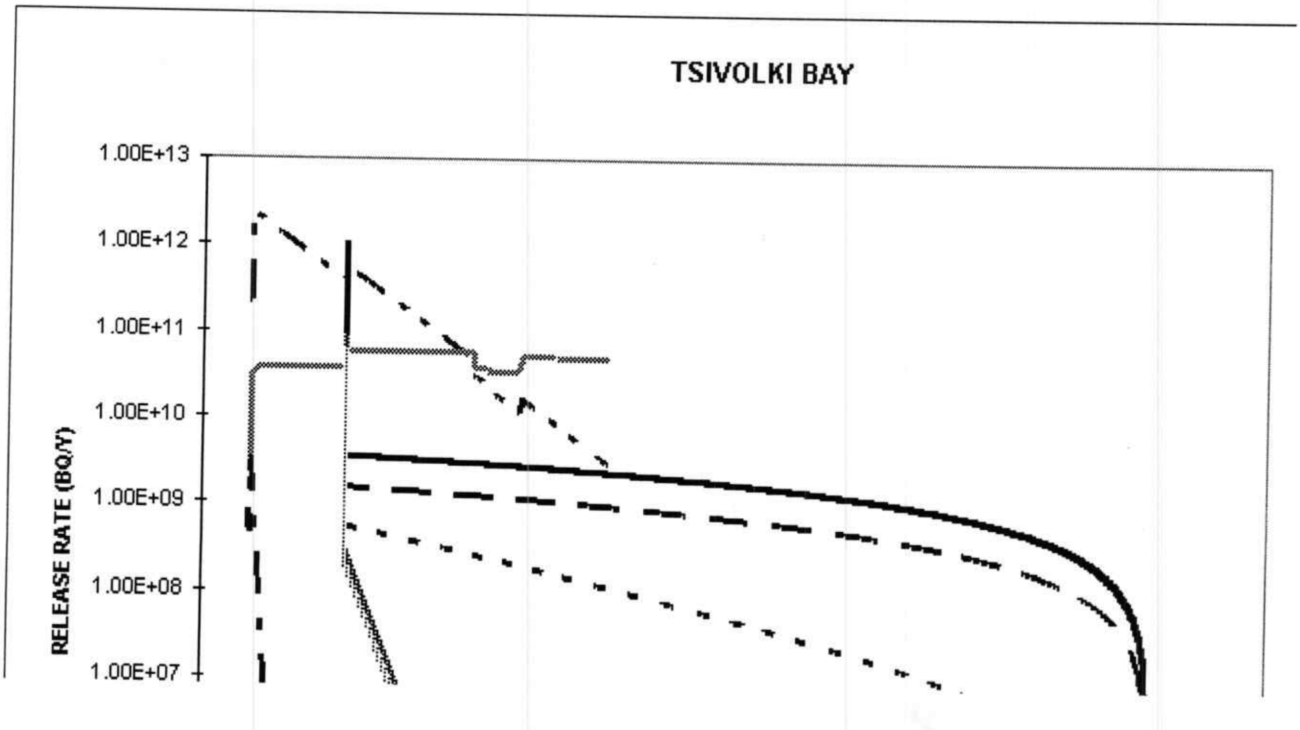
The contamination of fish, crustaceans and molluscs is calculated from the radionuclide concentrations in filtered seawater in the different water regions. For this purpose, concentration factors for biological material are used. Data for the world catch of seafood in the various regions have been compiled from the Marina Study [2] and FAO [8]. The following assumptions for the edible fractions of seafood catch are used: 50% for fish, 35% for crustacea and 15% for molluscs. Collective doses to the world population are based on the ingestion of seafood only. Critical groups have been assumed located various distances from the dump sites: on the Yamal peninsula at the Kara Sea, on the Kola peninsula at the Barents Sea and in northern Norway. The following assumptions have been made for their habits for the estimation of radiation doses: ingestion of fish (200 kg y^{-1}), crustaceans (50 kg y^{-1}) and molluscs (50 kg y^{-1}); exposure to external gamma radiation for 250 h y^{-1} in coastal areas; and inhalation for 2000 h y^{-1} of resuspended beach sediment and seaspray at concentrations of 0.25 μ g m^{-3} and 10 g m^{-3}, respectively. Furthermore, a hypothetical critical group of military personnel staying at the bays with dumped nuclear waste has been included. The exposure pathways of this group, however, cover inhalation and external exposure from beach occupancy only.

Source terms

The source terms used for the calculations were obtained from the IASAP project. The best-estimate release scenario was selected comprising release rates of radionuclides from shallow bays on the east coast of Novaya Zemlya (Abrosimov Bay and Tsivolki Bay) and from the deeper waters of the Novaya Zemlya Trough. The radionuclide specific releases considered are shown in Table 1, and Fig. 2 shows the release rate assumed for the Tsivolki Bay where the reactor compartment and spent nuclear fuel from the Lenin icebreaker was dumped in 1967. The graph shows that the best-estimate scenario assumes release of the activation products only (Co-60, Ni-59, Ni-63) until the year 2300 due to corrosion of the protective barriers. At that time contact is assumed between the seawater and the spent nuclear fuel, and a peaked release of fission products (Cs-137 and Sr-90) and transuranics (Pu-239, Pu-240, Am-241) is assumed followed by a steady release due to corrosion of the nuclear fuel.

Table 1. Integrated release of radionuclides (TBq) dumped in the Kara Sea, IASAP best-estimate scenario.

	Tsivolki Bay	Abrosimov Bay	Novaya Zemlya Trough
Pu-239	4.9	0.73	0.09
Pu-240	2.1	0.32	0.04
Am-241	0.41	0.12	0.01
Co-60	0.03	2.9	0.08
Ni-63	370	110	1.9
Ni-59	40	110	2.3
Cs-137	0.10	41	8.7
Sr-90	0.07	34	7.4



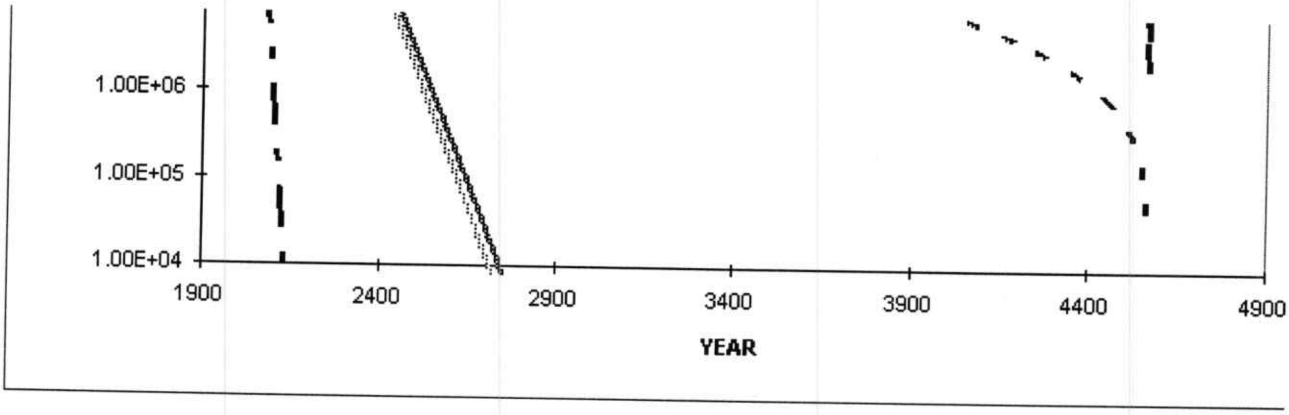


Figure 2. Radionuclide release rates (TBq y^{-1}) for Tsivolki Bay estimated by the IASAP Source Term Group.

Parameters investigated

The parameter sensitivity of the doses to individuals and populations has been investigated concerning three main processes: water movement and mixing, sediment-water interaction and biological transfer. For the hydrodynamical processes, four parameters were investigated: the advection and mixing between the Kara Sea and the Laptev Sea to the east, the advection and mixing between the Kara Sea and the Barents Sea to the west, the vertical mixing between surface and deeper waters over the Novaya Zemlya Trough, and the rates of exchange of water between the bays containing the dumped waste and the open Kara Sea. The sediment-related parameters were the following: sedimentation rates, sediment distribution coefficients (K_d), suspended sediment loads, depth of the mixed surface sediment layer, and the mixing rates in the surface sediments. For the biological transfer processes, the three parameters representing biological concentration factors for fish, crustaceans and molluscs were included.

The parameter sensitivity analysis was carried out by assigning identical variabilities of 10% to all the above mentioned parameters and running the model repeatedly (about 500 times). Correlation coefficients were calculated between parameter values and dose values, and the square of the correlation coefficients (R^2) were interpreted as how much of the variation of the doses is explained by the linear relationship to the parameters. The parameter sensitivities are thus expressed in percent of the total variability.

Results

Collective doses

The results of the parameter sensitivity analysis for the collective doses are shown in Table 2 which summarises the integrated releases, the collective doses and the main parameter sensitivities (> 1%). The total collective dose is calculated to 0.4 manSv (truncated at 1000 y) with dominating contributions from plutonium isotopes of 57% and from Cs-137 of 37%. The parameter sensitivities are seen to vary across the radionuclides from Sr-90 which has a low K_d to the transuranics and activation products which have high K_d's. For the total collective dose the main parameter sensitivities are due to sedimentation processes (sedimentation rate, K_d, suspended sediment load) and biological transfer processes (concentration factor for fish). Furthermore, it is noted that the collective dose is very small.

Table 2. Integrated releases (TBq), collective doses (manSv) and main parameter sensitivities (%).

Nuclide	Cs-137	Sr-90	Pu-239	Pu-240	Co-60	Am-241	Ni-63	Ni-59	Total
Total release (TBq)	49	42	6	2.4	3	0.5	480	150	
Coll. dose (manSv)	0.14	0.02	0.16	0.06	7E-05	0.001	0.002	0.001	0.4
Coll. dose (%)	37	5	41	16	0.02	0.4	0.6	0.3	100
Sedimentation rate, (%)	19		66	66	54	61	53	53	45
Conc. factor, fish (%)	65	90			13		4	4	28
K_d (%)	11		13	13	25	7	24	24	12
Susp. sediment load, (%)			16	16	4	14	1	1	9
Conc. factor, molluscs (%)			9	9		5	1	1	5
Adv., Kara Sea, west (%)	4	1					4	4	2

Individual doses

The results of the parameter sensitivity analysis for the maximum annual doses to individuals in the critical groups are shown in the Tables 3 to 6 which summarise the dose rates from each nuclide and the main parameter sensitivities (> 1%). For all the critical groups, the time of occurrence of the maximum dose rate is related to the peaked release of radionuclides from Tsivolki Bay at year 2300 when the protective barriers of the spent nuclear fuel from the Lenin icebreaker are penetrated due to corrosion. The late occurrence of that event means that the shorter-lived fission products Cs-137 and Sr-90 have decayed and that the transuranics dominate the release. These radionuclides associate readily with sediments for what reason the main parameter sensitivities for long range transport are related to sedimentation processes (e.g. sedimentation rate, K_d, suspended sediment load). The advection and mixing of water from the Kara Sea to the Barents Sea also has some influence on the maximum dose rates to the critical groups in northern Norway and on the Kola peninsula. The maximum dose rates to these groups are very low (of the order of about a nanosievert per year).

Table 3. Maximum dose rates (Sv y^{-1}) in year 2300 to a critical group in northern Norway and main parameter sensitivities (%).

Nuclide	Cs-137	Sr-90	Pu-239	Pu-240	Co-60	Am-241	Ni-63	Ni-59	Total
Dose rate (Sv/y)	7E-13	7E-14	2E-10	8E-11	0E+00	2E-11	5E-14	5E-15	3E-10
Dose rate (%)	0.2	0.0	64	28	0.0	7	0.0	0.0	100
Sedimentation rate (%)									43
Adv., Kara Sea, west (%)									15
Kd (%)									14

Conc. factor,molluscs (%)	10
Bay flushing rate (%)	7
Susp. sediment load (%)	5

Table 4. Maximum dose rates (Sv y^{-1}) in year 2300 to a critical group on the Kola peninsula at the Barents Sea and main parameter sensitivities (%).

Nuclide	Cs-137	Sr-90	Pu-239	Pu-240	Co-60	Am-241	Ni-63	Ni-59	Total
Dose rate (Sv/y)	7E-12	6E-13	2E-09	7E-10	0E+00	1E-10	4E-13	5E-14	3E-09
Dose rate (%)	0.3	0.0	66	29	0.0	4	0.0	0.0	100
Sedimentation rate (%)									34
Kd (%)									21
Adv., Kara Sea, west (%)									20
Conc. factor, mollusc (%)									11
Bay flushing rate									9

For the critical group on the Yamal peninsula at the Kara Sea, the concentration factor for molluscs and the bay flushing rate have higher sensitivities than those of the sediment-related parameters. This is because the Kara Sea is the first recipient of the radioactivity from the Tsivolki Bay. The maximum dose rate to the critical group is very low, of the order of about a microsievert per year.

Table 5. Maximum dose rates (Sv y^{-1}) in year 2300 to a critical group on the Yamal peninsula at the Kara Sea and main parameter sensitivities (%).

Nuclide	Cs-137	Sr-90	Pu-239	Pu-240	Co-60	Am-241	Ni-63	Ni-59	Total
Dose rate (Sv/y)	2E-09	1E-10	7E-07	3E-07	0E+00	1E-07	2E-10	2E-11	1E-06
Dose rate (%)	0.1	0.0	63	28	0.0	9	0.0	0.0	100
Conc. factor, mollus (%)									32
Bay flushing rate (%)									31
Sedimentation rate (%)									20
Kd (%)									15
Conc. factor, crustac (%)									3

For the critical group located at the Tsivolki Bay only external exposure and inhalation pathways are considered. Inhalation dominates due to the transuranic nuclides. The most sensitive parameter is the sediment mixing depth which shows a strong negative correlation with the dose rates and a high sensitivity (56%). This is due to the association between sediments and transuranic elements, for what reason the transuranic elements are removed by sedimentation from the water column to the sediment where the concentration (activity/volume) depends on the value of the sediment mixing depth. A small sediment mixing depth gives a small sediment volume and a high sediment concentration from which resuspension causes high doses due to inhalation. The maximum exposure of the critical group is estimated to an annual dose of the order of about ten millisieverts per year.

Table 6. Maximum dose rates (Sv y^{-1}) in year 2300 to a hypothetical critical group located at the Tsivolki Bay and main parameter sensitivities (%).

Nuclide	Cs-137	Sr-90	Pu-239	Pu-240	Co-60	Am-241	Ni-63	Ni-59	Total
Dose rate (Sv/y)	1E-07	4E-07	5E-03	2E-03	0E+00	6E-04	7E-09	6E-10	7E-03
Dose rate (%)	0.0	0.0	64	28	0.0	8	0.0	0.0	100
Sedim. mixing depth (%)									56
Kd (%)									18
Bay flushing rate (%)									10
Sedimentation rate (%)									9
Susp. sediment load (%)									3

Conclusions

A parameter sensitivity analysis has been carried out for a radiological assessment model used for prediction of doses to man from dumping of radioactive waste in the Kara Sea. The model covers the Arctic and Atlantic Oceans and calculates doses to the world population as well as to critical groups from a range of exposure pathways. Release rates of radionuclides from waste dumped in the Kara Sea have been used as source terms. These data were made available from the International Arctic Seas Assessment Project of the International Atomic Energy Agency. The sensitivity analysis has focused on three areas: hydrodynamical processes, water-sediment interaction processes, and biological transfer processes. The doses to man are generally dominated by contributions from long-lived transuranic radionuclides (plutonium and americium isotopes) which associate readily with sediments. For that reason the sediment-related processes and parameters generally show high sensitivities, particularly where doses are delivered some distance from the dump sites, e.g. in the Barents Sea. At closer distances, in the Kara Sea and in the Novaya Zemlya bays, biological transfer and hydrodynamical processes show high sensitivities. This study illustrates that more detailed information on sediment-related processes, biological transfer processes and hydrodynamical processes in the Arctic waters will help reduce the predictive uncertainty of the dose assessment.

Acknowledgements

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