Regional probabilistic nuclear risk and vulnerability assessment by integration of mathematical modelling and GIS-analysis

Olga Rigina[1,3] and Alexander Baklanov[2] *

[1] Institute of Geography, University of Copenhagen, Østervoldgade 10, DK-1350 Copenhagen K, DENMARK
[2] Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen Ø, DENMARK
[3] Institute of the Northern Ecology Problems, 14 Fersman, 184200 Apatity Murmansk reg., RUSSIA

Abstract

The Kola Peninsula, Russian Arctic exceeds all other regions in the world in the number of nuclear reactors. The study was aimed at estimating possible radiation risks to the population in the Nordic countries in case of a severe accident in the Kola Peninsula. A new approach based on probabilistic analysis of modelled possible pathways of radionuclide transport and precipitation was developed. For the general population, Finland is at most risk with respect to the Kola NPP, because of: *high population density or proximity to the radiation-risk sites and *relatively high probability of an airflow trajectory there, and precipitation. After considering the critical group, northern counties in Norway, Finland and Sweden appear to be most vulnerable.

Key words: Kola Peninsula, Nordic countries, nuclear reactors, residential risk, vulnerability

Introduction

The Kola Peninsula of Russian Arctic exceeds all other regions and countries in the world in number of nuclear reactors. Bergman and Baklanov (1998) classified the Kola NPP and nuclear submarines at refuelling as high-risk objects regarding radiological consequences. For risk assessment close to a NPP zone, numerical modelling methods have been actively developed (PSA 1995, MACCS 1990). However, on the regional scale, and for complex assessments of risk, especially including social and regional aspects, such approaches are either under elaboration or cover only some aspects of risk. GIS-based analyses integrated with mathematical modelling allow to develop a common methodological approach for complex assessment of regional vulnerability and residential risk, by merging together separate aspects: modelling of consequences, probabilistic analysis of pathways, dose estimation etc.

The purpose of this study was to develop a methodology for complex nuclear risk and vulnerability assessment and to estimate possible radiation risk to the population in the Nordic countries in case of a severe accident at the Kola NPP.

* Corresponding author: DMI, Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark; fax +45 39157460; e-mail: alb@dmi.dk

Materials and methods

Numerical modelling

Numerical modelling is widely used to study long-range airborne transport and deposition of radioactive matter after a hypothetical accident. Depending on scale and consequences of interest, different models can be used.

1. For probabilistic analysis (atmospheric transport pathways, airflow and precipitation probability), isentropic trajectory model (Merrill 1994) and cluster analysis technique (Mahura et al., 1999; Baklanov *et al.* 2000) were used.

For the airflow probability fields, more than 233000 5-day forward trajectories that originated over the nuclear accident region for the period 1991-1995 were calculated (Jaffe *et al.* 1997; Baklanov *et al.* 2000). These fields show geographical variations of airflow patterns from the accident site. To account for the contribution of the possibility of radionuclide wet removal during the transport of an air parcel, the value of relative humidity was calculated simultaneously for each trajectory point (i.e. at latitude, longitude and pressure level point) (Baklanov *et al.* 2000). Based on the calculated temporal and spatial distribution of the relative humidity, precipitation factor fields were constructed over the geographical areas.

2. For long-term consequences for population after an accident, the MACCS (MACCS 1990) and empirical models based on the Chernobyl effects on Scandinavia (OCDE 1987; Hägg 1990; Moberg 1991; Dahlgaard 1994) were applied.

Probabilistic social-geophysical risk

A vulnerability analysis identifies the geographic areas and populations susceptible to damage or injury in case of an accidental release (Lowry *et al.* 1995). In contrast to risk in the Probability Safety Assessment, in our probabilistic approach, 'risk' is some complex characteristic of vulnerability of different territories with respect to the Kola NPP or other nuclear risk sites.

For estimation of consequences of radiation impact to Man, we will proceed from the official conception of IAAE (1987). This conception supposes a non-threshold linear dependence between dose and effect. Any level of radiation is considered as harmful.

For assessment of risk/vulnerability we consider the social-geophysical *factors*, which depend on the location of the area of interest and its population: proximity to the radiation risk sites; population density in this area; presence of critical groups of population; and *probabilities*: probability of an accident of a certain severity at the radiation risk sites; probability of air transport pathways towards the area of interest from a risk object (from probabilistic trajectory modelling); probability of precipitation over this area during the transport of the plume along the trajectory (from probabilistic modelling).

For estimation of vulnerability/risk for different regions, let us introduce a risk function defined as a complex index of probability of risk for different factors. Let us define this risk function R_i from the Kola NPP for an administrative unit by two different methods. The first method supposes multiplication of different factors and probabilities (all P and F will be defined later):

$$R_i = P_{acc,i} P_{tr,i} P_{pr,i} F_{dem} F_{dis,i} F_{t,i} F_{cg} F_{soc} F_{ev} . \quad (1)$$

The second method doesn't have a clear physical interpretation, but is widely used in various risk/vulnerability studies (Lowry *et al.* 1995; Obee *et al.* 1998). It supposes a weighted sum of the above-mentioned factors of different nature. We suggest an alternative approach that involves the multiplication of a number of risk probabilities and a weighted sum of other factors. This allows for attributing different importance to the risk factors, yet introduce an element of uncertainty associated with the subjective choice of weights:

$$R_i = P_{acc,i} P_{tr,i} P_{pr,i} (a_1 F_{dem} + a_2 F_{dis,i} + a_3 F_{t,i} + a_4 F_{cg} + a_5 F_{soc} + a_6 F_{ev}) . \quad (2)$$

In (1) and (2), P_{acc} is a function defining probability P_k of an accident of a certain class k and severity I_k: $P_{acc} = \sum_{k=1}^{m} P_k I_k$ (In this study, we, however, assume that an accident has happened, i.e. $P_{acc} = 1$).

P_{tr} is a probability that the trajectory of the accidental plume will reach a certain territory (area of interest). In our case we consider a probability of passing the trajectory through a territory of 2.5 degree x 2.5 degree size (Jaffe *et al.* 1997).

P_{pr} is a probability of precipitation over a certain territory during the plume pass. In a general case, wet deposition - being determined by precipitation - can be included as a factor controlled by the intensity of precipitation. In our case, the factor of wet deposition is determined by relative humidity during passing the air masses through a territory (Baklanov *et al.* 2000). So, it is advisable to consider it as a function of probability. Let us assume that the probability of precipitation, P_{pr}, is 0 for a relative humidity, q, less or equal to 50%, and 1 for q = 100%.

F_{dis} is a factor, representing dispersion and dry deposition of the radioactive plume on its way from the accident site. Different long-range transport models (ADPIC, DERMA) or a simpler empirical function of distance can be used for its definition. Let us define F_{dis} as a function of distance and dispersion parameter σ according to the Gaussian equation at short distances (< 100 km) and as a polynomial on a basis of numerical experiments by the model DERMA (Sørensen 1998; Baklanov 1999) at a regional scale (> 100 km). And let us scale F_{dis} to 1, normalising it by the maximum concentration, found close to the accident site.

F_{dem} is a population factor for the general group. For method 2, let us define this factor as population density, scaled so that $F_{dem} = 1$ in the areas with the maximum population density and $F_{dem} = 0$ for inhabited areas. Since we use population density, we will classify the result as vulnerability of a territory with respect to the Kola NPP or other radiation risk site. In method 1 we use the number of people, rather than population density. Collective and individual risk is calculated analogous to the collective and individual doses.

F_t is a function defining risk connected to a quick transport of contamination, and it is inversely proportional to the time for reaching a certain territory by the plume. Let us initially set it to 1, because it is already indirectly included in F_{dis}. However, it is advisable to include this factor in the analysis for emergency preparedness to stress the quick impact.

F_{cg} is a factor defining vulnerability of the critical groups of the population to radioactive contamination. Let us define it as a function proportional to the population density of critical groups D_{cr} normalised by the population density for the general population D_g and a ratio of risk/criticality for a critical group r_{cg} : $F_{cg} = r_{cg}\, D_{cr} / D_g$, where r_{cg} is defined as the ratio of the individual dose for a critical group to the individual dose for the general population based on experimental data of the Chernobyl effects on Scandinavia. In this study we consider only one critical group of the population - reindeer-herders, constituted generally by aboriginal Saami in Lapland. The ratio r_{cg} for different areas of the north of Norway, Finland, Sweden and the Murmansk region varies from 40 to 100 based on the Chernobyl data (AMAP 1998).

F_{soc} is a factor of social risk, which depends on risk perception, preparedness of safety measures, systems for quick reaction, economical and technical means, counteracting consequences of a possible accident etc. This factor can be defined for the administrative units in accordance with some scale by subjective estimation or a set of criteria. However, in this study it was not included.

F_{ev} is a factor defining ecological vulnerability of an area. Cumulative intake of radionuclides by Man can be estimated based on models of different complexity (Balonov *et al.* 1999) through effectiveness of transfer in the food chains within specific ecosystems and consumption of various food. In this case, it is necessary to include new GIS layers of soil, vegetation, consumption habits etc. into the database. Now we are not going into details with this aspect of risk, because it will be a task for further consequence analysis (Bergman and Ågren 1999). Methodical approach based on critical loads to recognise ecologically sensitive (to radioactive contamination) territories is actively developed within the bounds of the AMAP program.

The weight coefficients a_i vary depending on the relative importance of each of the factors. These weights introduce a main difficulty and an uncertainty in the analysis, because there is a summation of the factors of different nature.

The correctness or appropriateness of the suggested formulations is indirectly supported: considering fewer factors of the similar nature (i.e., in a limit or asymptotic case), we obtain the known and approved dependencies. I.e., the novelty of the suggested method is in generalisation of the known methods at the expense of the introduction of new factors of different nature and, from the other side, in simplification of the relations for each factor.

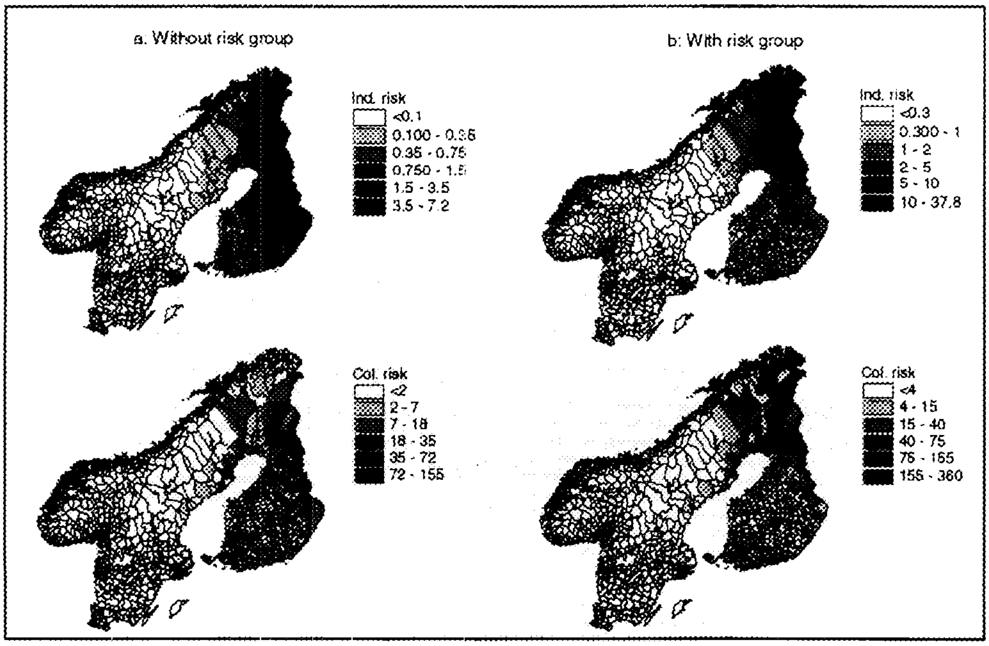

Figure 1. Map of probabilistic risk (relative units) from the Kola NPP to the population in the Nordic countries estimated by method 1.

GIS-analysis for risk and vulnerability assessment

A GIS provides a powerful tool for analysing the relationship among different factors in order to assess risk/vulnerability for the Nordic countries at administrative level (community, county, country). First, the modelling results showing probability for atmospheric pathways and precipitation during the transport were exported to the GIS format for producing several thematic layers. The population data at administrative level for the Nordic countries were obtained for 1996. Then each layer was georeferenced to the basic map (in geographic projection) by an affine transformation using tics.

The population density was derived for each administrative unit from the population attributive table by normalising the population number by the area. The thematic layers were joined with the administrative data by means of the Spatial Join module (within Arc/Info). As a result, new features such as the probabilities, and proximity to the nuclear site were assigned to each administrative unit. In case, when an administrative unit didn't fall within one class, the attribute was calculated as an area-weighted sum.

Composite Mapping Analysis (CMA) is based on the GIS overlay method, but applies adding, multiplying, scaling and weighting of the GIS layers. A GIS-based CMA integrates a wide range of risk-site-related and human-related factors that affect the territorial vulnerability and thus was used for probabilistic vulnerability assessment.

Results

Figure 1 shows maps of the collective and mean individual risks from the Kola NPP for the population of the Nordic countries by administrative unit, estimated by method 1. For general group of population, Finland appears to be at highest residential risk, because of either relatively high population density or proximity to the radioactive risk site, coupled with a relatively high probability of both airflow trajectories and precipitation. Figure 2 shows a map of the estimated by method 2 vulnerability of different administrative units in the Nordic countries with respect to the Kola NPP. Despite different approaches, both methods have revealed the same administrative units (counties) as the most vulnerable or the units where population is at most risk. In the 1st method, risk is divided in collective and mean individual risk, whereas in the 2nd method the population factor was accounted for by using a population density for each group.

Although the critical group - saami (reindeer-herders) is small, after taking it into account, the collective- and mean individual risk patterns have changed towards dominance of the northern counties, such as Finnmark in Norway, Lappland in Finland and Norbotten in Sweden. For example, in the most saami-dominated commune Finnmark in Norway, the mean individual risk increases from 0.59 to 10.08, whereas the collective risk elevates from 63 to 1090 after taking the critical group into account.

For the general population group, along with the northern counties, the county Uleåborg is also subject to high risk because of high population density.

In Figures 1 and 2, the scale for the risks should be understood in a relative way. For example, the county Uleåborg is at twice higher risk compared to the county Lappland with respect to summary collective risk (method 1, column 2), or Finland in general is at 10-times higher risk compared to Norway and Sweden (method 2, column 8). The absolute values of the estimated risk are not important in this context. In reality, the absolute risk and severity of a situation will be defined by the parameters of the release. For example, in case of a release of 1 PBq, the deposition, dose and absolute risk (expressed, for example, in mortality) can be very low compared to a release of 60 PBq under the same other conditions, whereas the relative proportion between risks for Finland and Sweden, for example, will remain about the same.

Also, these estimations outline possible worst-case situation: a person can remain at home and thus will not get the highest dose, or special rescue measures will be undertaken in time (withdrawal radioactively contaminated food and goods from use, early warning, treatment with medicine, evacuation).

Estimation of the probabilistic complex risk can be illustrated for the limit cases, when certain probabilities are set to 1. If for a certain territory, for example, Västerbotten county in Sweden, we set the probability of trajectory there from the Kola NPP to 1, the probability of precipitation there is also equal to 1, then in case of a unit release (1 Bq) of ^{137}Cs the mean deposition of radionuclides will be equal to $1.5 \cdot 10^{-12}$ Bq/m^2. Correspondingly, in case of a release of 10 PBq, the deposition will be ca 15 kBq/m^2. Taking the factors of population and critical groups for Västerbotten into account, the mean collective dose for population by unit area (km^2) will be $5.7 \cdot 10^{-4}$ manSv/km^2, and the mean individual dose will be 0.132 mSv, and total collective dose will form 34 manSv. This risk is comparable with the mean deposition of ^{137}Cs and the radiological consequences from the Chernobyl in this county of Sweden. This method can be used for verification of the optimal scaling and weighting coefficients for various factors.

Conclusion

1. For the general population group, a large part of Finland is subject to high risk with respect to the Kola NPP, because of high population density or proximity to the radiation risk sites coupled with a rather high probability of atmospheric pathways there with precipitation during the transport.

2. Although the critical group - saami (reindeer-herders) is small, taking it into account implies that the collective- and mean individual risk patterns change towards the dominance of the northern counties: Finnmark (No), Lappland (Fi) and Norbotten (Sw).

3. The integration of the GIS-analysis and mathematical modelling is a very successful and flexible tool for a complex risk assessment.

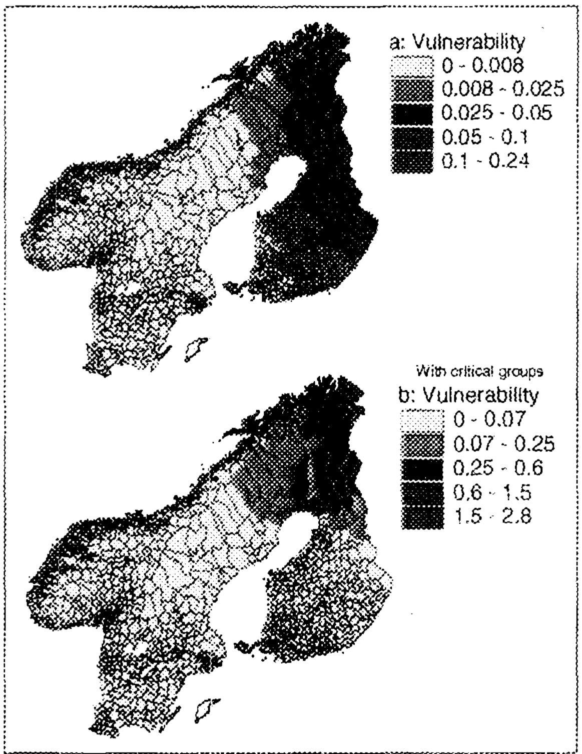

Figure 2. Map of vulnerability (relative units) by administrative unit in the Nordic countries in respect to the Kola NPP estimated by method 2.

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