Integrated Analysis of Accident Scenarios, Radiological Dose Estimates and Protective Measures Efficacy Following a Radioactive Release

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INTRODUCTION

A nuclear accident may result in radioactivity being directly released to the atmosphere, to rivers, to the sea and to the ground. The main threat to urban areas and their inhabitants is generally considered to be from releases to the atmosphere, which are then carried over and deposit their radioactivity on towns and villages. The radiological assessment of the consequences of an accidental release of pollutants is an important tool for an emergency decision-making process, especially during the early and intermediate phase of an accident in which radioactive materials escape from the installation into the environment. The development and evaluation of adequate protective measures are part of the decision-making process and have to be concerned with several components. Among them, the technical and scientific components, such as the knowledge of the source-term (features of the release), availability of meteorological data, modeling of atmospheric dispersion, modeling of deposition and modeling of exposure (and health effects, if required). However, the social and economical components are also very specific for each region and need to be carefully considered.

Internationally, safety analysis studies ensuring that the public and the environment are adequately protected, are a requirement to obtain the permission for the operation of a nuclear power installation (operation license). More recently, a considerable amount of effort has gone into developing more realistic methods to fulfill the safety requirements. In addition to a huge amount of data gathered from studies during the pre-operational phase, up to the construction and operation of the power plant, there has also been a considerable development of environmental analysis techniques These techniques demand an integrated approach taking into account all the relevant information to provide a better knowledge of the potential environmental impact associated with hypothetical accident scenarios in those plants.

All these developments have led to an increasing demand for greater levels of geographical data analysis and mapping procedures in the planning and implementation of major decisions, and also for the monitoring and evaluation of the results of these decisions. Geographic information systems (GIS) is an efficient method for storing information about complex relationships and plays an important role to improve the user's ability to make decisions in research, planning and management.

This study is concerned with the application of this integrated approach in the planning and selection of protective measures to protect the public in the case of an accidental release of radioactive material into the atmosphere. A very simple methodology was established taking the Brazilian nuclear power plant site as a case-study. By selecting a hypothetical accident for a generic pressurized water (PWR) to define the source-term, it is possible to estimate the radiation dose to the public. This layer of information is integrated to other layers of information related to specific environmental, demographic, social and economic features of the region where the plant is located. The objective of this approach is the identification and a previous selection of areas requiring a more detailed planning for the establishment of protective measures.

DISCUSSION

Background

Dose Estimates

The first consequence analysis study of nuclear power plant operation was introduced in the middle 70's: the Reactor Safety Study (WASH-1400).[1] In this publication, nine accidental-release categories and their respective source-term are described. After the accident in Three-Mile Island, further studies presented a much lower fraction of radionuclides in the source-term, indicating that a conservative approach had been adopted by the first study. However, in spite of these studies, the categories described by the WASH-1400 are still used as a technical basis for decision-making procedures.

The category selected for the purpose of this study is classified as PWR-4, which is described by a sequence of events leading to serious accident, including core melting and failure in the containment building. According to Dolores [2], the description of the PWR-4 category shows many similarities to those defined as BEED (Best Estimate from Empirical Data). Presently, the BEED category is considered the most reasonable one, as compared with empirical data available. Once defined as the source-term, the radiation dose can be estimated for different distances from the source.

Local Factors

In addition to dose estimates and local environmental factors, the establishment of a set of protective measures following a radioactive release, also depends on characteristics of population including social and economical conditions. In general terms, these factors can be listed as below:

1) Existence of groups of population
2) Distance from the emission source
3) Communication
4) Means of transport

5) Adequate roads or via of transport
6) Existence of appropriate shelters

The existence or absence of population is an important factor in the evaluation of the area to receive the first basic protective measures. The number of people in the different villas or groups will influence in some way the application of different protective measures. The higher the population, the higher the resources required for the implementation of protective measures. In another way, a high number of people could cause for example, a traffic jam in the case of an evacuation measure.

The distance of the emission source is an essential factor to be considered, since the accident-related dose is proportional to the distance. The application of certain protective measures is only required above a defined limit, below which no action is taken.

Communication capacity is related not only to the possibility of communication, via equipment of radio, TV, etc, but also to the capacity of understanding the situation as an emergency.

The existence of adequate roads and means of transport are especially important in the case of evacuation of people from the affected areas.

The shelters in the areas should be considered under two aspects: 1) as a shelter against bad weather conditions, allowing people to wait for further transferring or additional information; 2) as a radioactive shelter, reducing the radiation exposure and ingestion of radioactive material.

Case-Study

A brief description of the study-site and population characteristics are presented in the next paragraphs, giving emphasis to some aspects of geography, meteorology and population.

Local Characteristics

The study-site is located at the southeastern coast of Brazil (23.0° S, 44.5° W) about halfway between Rio de Janeiro and Santos (state of São Paulo). It is a bowl-shaped area with hills on three sides and a bay on the fourth side. The highway Rio de Janeiro-Santos (BR101) is directly beside the northern and eastern fences of the nuclear power plant site (NPP). The curved shoreline is oriented NWW to SSE with the bay to the west. To the north of the NPP and the highway, there are bluffs rising up to 700 m and to the southeast of the NPP hills rise to less than 300 m. Generally speaking, 50% of the area is occupied by hills and 50% by ocean. The hills are covered with a tropical forest of a dense canopy (Mata Atlantica). Local wind-systems and turbulence are complicated by the land-sea interface and high insolation due to low altitude. The region is also characterized by intense precipitation, low average wind speeds (about 1.5 m/s) and stable atmosphere (Pasquill class E). Agricultural and fishing activities are mainly of subsistence nature. Spotty cattle are raised on small-scale. The industrial activity is basically non-existent. Boating and swimming activities are practiced by the small population and by an increasing number of tourists during certain periods of the year [3].

Population

The site region is sparsely populated by small villages along the coast. According to a recent local census, a population of 10,804 people live within the area of 5 km around the NPP. Three categories can be used to describe the population:

Workers: all the individuals who work in the operation of the unit 1 and those involved in the construction of the unit 2. They are considered a special group of people who remain in the plant site on a daily basis. Presently, there are about 4000 workers in the NPP.

Permanent inhabitants: all the individuals who live permanently in the area. They are mainly concentrated in 3 areas: Residential Vila of Praia Brava (2102 inhabitants) fully occupied by workers and their families, as well by local people running small businesses in the area; Frade (2,354 inhabitants) and Cunhambebe (1,849 inhabitants).

Eventual inhabitants: mainly tourists, who spend the weekends and holidays in the region. Porto Frade and Praia Vermelha are the most popular resorts.

Most of the local population (98%) within the 5km radius, has some level of literacy, with only 2% illiteracy. In general terms, it can be said that the local population have a certain level of participation and a reasonable understanding of the NPP activities. Educational and information campaigns have been carried out by the plant operator. The installation of the plant in the region has also been an important source of employment.

Source-Term

Table 1 presents the probability of occurrence of the accident category PWR-4 including periods of time involved during the release of material and fraction of total inventory of fission products released into the atmosphere. Having defined the accident category, the dose estimates can then be evaluated using a proper code.

Table 1. Source-Term (PWR-4)

Probability and time					Fraction of the total inventory of fission products released from the core						
Probability/ reactor.year	Time(1) (h)	Dur(2) (h)	Adv(3) (h)	Energy 10^6Btu/h (7)	Xe, Kr	I	Cs, Rb	Ba, Sr	Ru	La
4×10^{-7}	2	3	2	1	1	0	0.04	5×10^{-3}	3×10^{-3}	4×10^{-4}

(1) Time interval between the beginning of the accident and the release of radioactive material into the atmosphere.
(2) Total time spent to release most of the radioactive material into the atmosphere
(3) Time interval between the acknowledgment of the release (to make the decision to apply protective measures) and the release of radioactive material into the atmosphere.

Scenario Analysis

Thyroid doses (4) were estimated for a range of distances up to 5 km from the source. The maximum doses are found within the range of 1-2 km from the plant, due to the release of heat energy in the considered accident category. Ground release, average wind speed of 1.5 m/s and Pasquill atmospheric stability class E were selected as being representative of the average conditions of the site. In addition, some other specific factors were established to identify those areas which need a further detailed investigation. Table 2 presents the factors which are considered in this integrated approach. Due to our limitation in terms of time, data availability and resources, some simplifications were made. However, the methodology can be applied to a wider range of scenarios or situations, taking advantage of more detailed information and resources available.

Table 2. Factors and weights adopted for the integrated analysis with GIS

Population	Weight	Thyroid dose (REM)	Weight	Commu nication	Weight	Shelte r	Weight	Roads	Weight	Means of Transport	Weight
100-500	1	25-50	1	yes	1	yes	1	yes	1	yes	1
500-1000	2	50-100	2								
>1000	3	>100	3								

As a starting point, it was considered that the selected areas should have at least 100 inhabitants. This limit was chosen due to the high number of very small localities scattered over the study region. Areas with a population higher than 1000 inhabitants were given the higher weight (3), since these areas would require a very well planned set of protective measures. The range of dose values shown in Table 2 were adopted as a result of the calculated dose distribution within a 5 km radius from the nuclear plant. Accessibility to any type of communication, capacity of understanding and existence of appropriate shelters were considered as being satisfactory (weight = 1) in the whole region, as well as the roads and means of transportation.

The integration of all the factors by using a GIS[5] has provided the identification of several areas falling into different categories. The areas showing the combination of the higher scores suggest the need of a prioritization in the investigation of adequate protective measures in the case of an accidental release of radioactive material into the atmosphere. The results could be summarized showing areas classified as having higher, intermediate and lower priorities. Figure 1 shows the location of these areas.

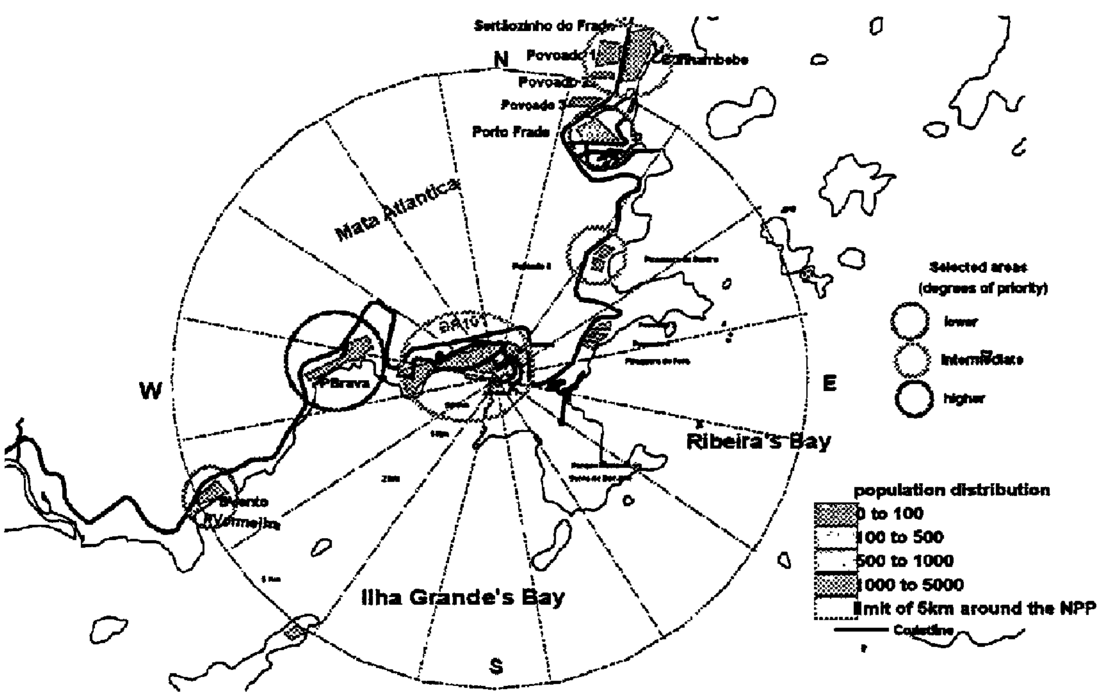

Figure 1. Study-area showing the location of the selected areas according to the criteria adopted by this study.

CONCLUSION

It was not the purpose of this work to exhaust all the possibilities of integration of information. A more detailed study would require the inclusion of additional relevant factors, improvement of dose estimates, meteorological data information, dispersion modeling, etc, would have to be introduced. However, even a simple approach has shown to be of great help by identifying critical areas in terms of planning of protective measures.

REFERENCES

(1) Nuclear Regulatory Commission-NRC, "Reactor Safety Study: An Assessment of Risk in U.S. Commercial Nuclear Power Plants", WASH-1400, (1975).

(2) Dorado, C. D., La Cruz , F. D. , "Estrategias de Actuacion en Emergencias Radiologicas", Energia Nuclear Espana 28 (1984)

(3) Furnas Centrais Eletricas, Final Safety Analysis Report, Central Nuclear Almirante Alvaro Alberto Unidade I, Capitulo 2.3 Meteorology, Diretoria Tecnica, Volume 1-2, Revisão 27, 1997

(4) Jow, H.N., J. L. Sprung, J. A. Rollstin, L. T. Ritchie, and D. I. Chanin, MELCOR Accident Consequence Code System (MACCS), Model Description, NUREG/CR-4691, SAND86-1562, Vol. 2, Sandia National Laboratories, Albuquerque, NM. (1990).

(5) CaliperTM, Caliper Maptitude User's Guide, version 3.0 for Windows, Caliper Corporation, (1995).

Information Synthesis for Aiding Recovery Decisions

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INTRODUCTION

As part of NRPB's role to provide advice on appropriate actions to take after an accidental release of radioactivity, tools are being developed and investigations are underway to enhance the quality and scope of information provided to decision makers. Particular emphasis is placed on information that helps in the consideration of potentially protracted countermeasures (i.e., food restrictions, decontamination and access restrictions (including relocation)). The potential long term social and monetary consequences of applying such countermeasures reduces the scope for precautionary application and increases the need for confidence in the information to be acted on. However, for both radiological protection and social considerations, there is likely to be pressure for these decisions to be made as soon as possible. Thus, there is a need for tools that maximise the information extracted from measurements and provide guidance on the likely consequences and acceptability of countermeasures.

This paper describes three projects currently in progress at NRPB. They form part of a multilevel approach towards providing decision making support. The final section reviews how the results of these independent projects may link together, to provide a scheme that will provide more nearly optimal guidance on the application of such countermeasures.

DISCUSSION

Characterising the Problem

A four-year research programme called SECTAR* (Statistical Estimation and Characterisation Techniques for Accident Response), is investigating techniques for assessing the extent of contamination from limited quantities of measurement data. Two complementary approaches are being followed to provide data driven estimates of the extent of any contamination. In the first case, measurements are used to adjust model estimates through a process of Bayesian updating.[1] This process enables a gradual shift of emphasis from model estimates to estimates based almost entirely on the measured values of contamination, as more measurements become available. The alternative approach investigates how to use a range of established geostatistical techniques, successful in a data rich environment, in the data poor environment occurring in the early stages of an accident.

The two approaches, Bayesian updating and geostatistical techniques, naturally meld with an increasing reliance on measurement data to correct and eventually supersede model estimates as the accident evolves.

To test alternative geostatistical techniques, predictions using subsets of measurements are compared with the reality represented by a more comprehensive data set. Rainfall and other correlated information, possibly gathered from models, may also be used to support estimates of the extent and amount of contamination where direct measurements are sparse. An objective is to find out what sorts of inferences can legitimately be drawn for a given sample size.

An example of what may be achieved using a very simple geostatistical approach is shown in Figure 1. This figure shows the result of applying ordinary kriging,[2] to a few measurements from the accident in 1992 at the Tomsk reprocessing factory in Russia.[3] The figure shows that a few points can give a good representation of the final contamination pattern. However, further work is underway on the conditions under which this is likely and the range of errors associated with estimates based on limited data. Ideally, what is sought is not only the best estimate for a given amount and configuration of sampling, but an estimate of how reliable that estimate is likely to be. A primary application of this information (combined with practicality considerations) will be to decide if implementing a countermeasure is appropriate, based on what is known, or to delay until more data are available.

A key aspect of these investigations is the collection of information on accidents from around the world. The use of real data is an essential prerequisite, if the anticipated improvement over non-adaptive modelling is to be demonstrated. Data from the accidents at Chernobyl, Tomsk and Windscale are currently in use or preparation.

Options for Removing the Problem

NRPB has recently published advice on a framework for decisions on decontamination and restricted access countermeasures ('recovery countermeasures').[4] The advice promotes a proportionate response and recognises the need to consider countermeasure strategies, rather than treating each protective action independently. The emphasis is on considering the full impact of the proposed strategy, in terms of resources, time, waste generation, environmental and social impacts and the averted dose. Strategies that can be finished quickly with relatively low adverse impacts, whilst also being radiologically effective, should always be considered (Category A). More disruptive, less practical, but still effective procedures should be additionally considered if the dose to a resident population is likely to exceed 10 mSv y^{-1} (Category B). Generally, options that have low radiological benefit, but relatively high adverse consequences (Category C) should only be considered if other measures are unable to reduce lifetime doses from the accident to below 1 Sv, or for non-radiological reasons. The advice is summarised in Table 1 below.

Table 1. Summary of NRPB advice on recovery countermeasures

	Countermeasures	
Circumstance	To consider	Unlikely to be justified
Any offsite contamination	Category A	Category B Category C[#]
Dose > 10 mSv y^{-1}	Category A, Category B[+]	Category C[‡]
Lifetime dose > 1 Sv	All	None

[#] Potentially justified in support of other measures.
[+] Need to offset increasing resource requirements/disruption with increasing dose averted; in general relocation would not be justified at doses around 10 mSv y^{-1}.
[‡] Potentially justified in support of other measures, or if Category B measures impractical.

It is within this context that decisions on strategies involving decontamination will be taken in the UK. A PC-based decision aid CONDO (CONsequences of Decontamination Options)* has been developed to illustrate the practical consequences that follow from selecting alternative decontamination procedures.

Use of CONDO requires the contaminated area to be specified as a series of regions defined by contamination level and environment type (i.e., the relative proportion of different types of surfaces). This information is combined with the results of a major UK review on the effectiveness of decontamination techniques[5] and precalculated dose consequences obtained from modelling[6], to provide the following endpoints: level of decontamination achieved; monetary costs; resources required; timescale; waste arisings and level of activity, residual doses and doses to clean-up workers. For perspective notional relocation costs are also provided.

Placing Countermeasures in a Social Context

There are complex problems of acceptability and compliance associated with the application of recovery countermeasures. Whilst, there are only a few categories of countermeasure, the way they are applied and supported can have large, and long term, consequences on their effectiveness. A project on Social Psychological Aspects of Radiation Protection after Accidents (SPARPA)* is investigating possible interactions between countermeasures, doses and some social and psychological factors in the former republics of the Soviet Union affected by the Chernobyl accident.

The aim of SPARPA is to develop a structural behavioural model that explains, to some extent, how particular behaviours and hence doses arise. This knowledge will help in the development of decision models that aid the selection of countermeasures and the strategy adopted to implement them. The work involves the use of focus groups, questionnaire surveys and individual dose measurements, with greatest attention being given to the consumption of private milk and free forest foods. Previous studies[7] indicate that these are the dose pathways most likely to help elucidate key properties in the relationship between the context in which countermeasures are applied and their success in reducing doses. Additionally, the provision of compensation payments and information campaigns are also under study. One particularly novel aspect of SPARPA is the consideration of why particular population groups may comply with restrictions and the distress this or its converse may cause.

Clearly, an ideal decision may be expected to minimise cost and distress while maximising the dose averted. However, it is likely that tradeoffs will have to be made and the understanding gained from SPARPA will provide guidance[8] on how best to achieve this.

CONCLUSION

Synthesis - The Way Forward

The three example strands of NRPB research and development are key elements in a more comprehensive approach to improving information for the decision maker. SECTAR aims to provide optimum estimates of what can be known for a particular amount of sampling and support information, together with an estimate of the range of results consistent with the data. This improved understanding of the likely extent of contamination supports programs such as CONDO that provide estimates of the consequences of applying countermeasures. Such consequences are in turn supported by considerations of the influence of social psychological factors in countermeasure decisions[9]. SPARPA provides methods to generalise the discussion on the influence of social psychological factors that will result in a broader decision aiding framework, that better understands the limitations of the data and the complexity of the options available.

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REFERENCES

1 O'Hagan, A, Kennedy, M C, and Oakley, J E. Uncertainty Analysis and other Inference Tools for Complex Computer Codes. Bayesian Statistics 6 (J M Bernardo, J O Berger, A P David and A F M Smith (Eds.) Oxford University Press, (1998).

2 Charnock, T W, Daniels, W M, Higgins, N A. Geostatistical Estimation Techniques Applied to Radionuclide Deposition: An Accident Response Decision Aid geoENV98 Nov. 18-20 Valencia (1998).

3 Shershakov, V M et al. Analysis and Prognosis of Radiation Exposure Following the Accident at the Siberian Chemical Combine Tomsk-7. Radiat. Prot. Dosim. 59(2) 93-126 (1995).

4 NRPB. Intervention for recovery after accidents. Doc. NRPB 8(1) 1-20 (1997).

5 Brown, J, Cooper, J R, Jones, J A, Flaws, L, McGeary, R, and Spooner, J. Review of decontamination and clean-up techniques for use in the UK following accidental releases of radioactivity to the environment. Chilton, NRPB-R288 (DOE/RAS/96009) (1996) (London, SO).

6 Crick, M J, and Brown, J. EXPURT A Model for Evaluating Exposure from Radioactive Material Deposited in the Urban Environment. Chilton. NRPB-R235 (1990).

7 Skryabin, A M et al. Distribution of Doses received in Rural Areas affected by the Chernobyl Accident. Chilton NRPB-R277 (1995).

8 Higgins, N A, and Morrey, M. Social intervention and risk reduction - indirect countermeasures. Radiat. Prot. Dosim., 68(3/4), 213-17 (1996).

9 Higgins, N A, Jones, K A, and McLaren, F E. An examination of consequences and recovery actions applicable in the recovery phase of a nuclear accident. Chilton, NRPB (to be published).

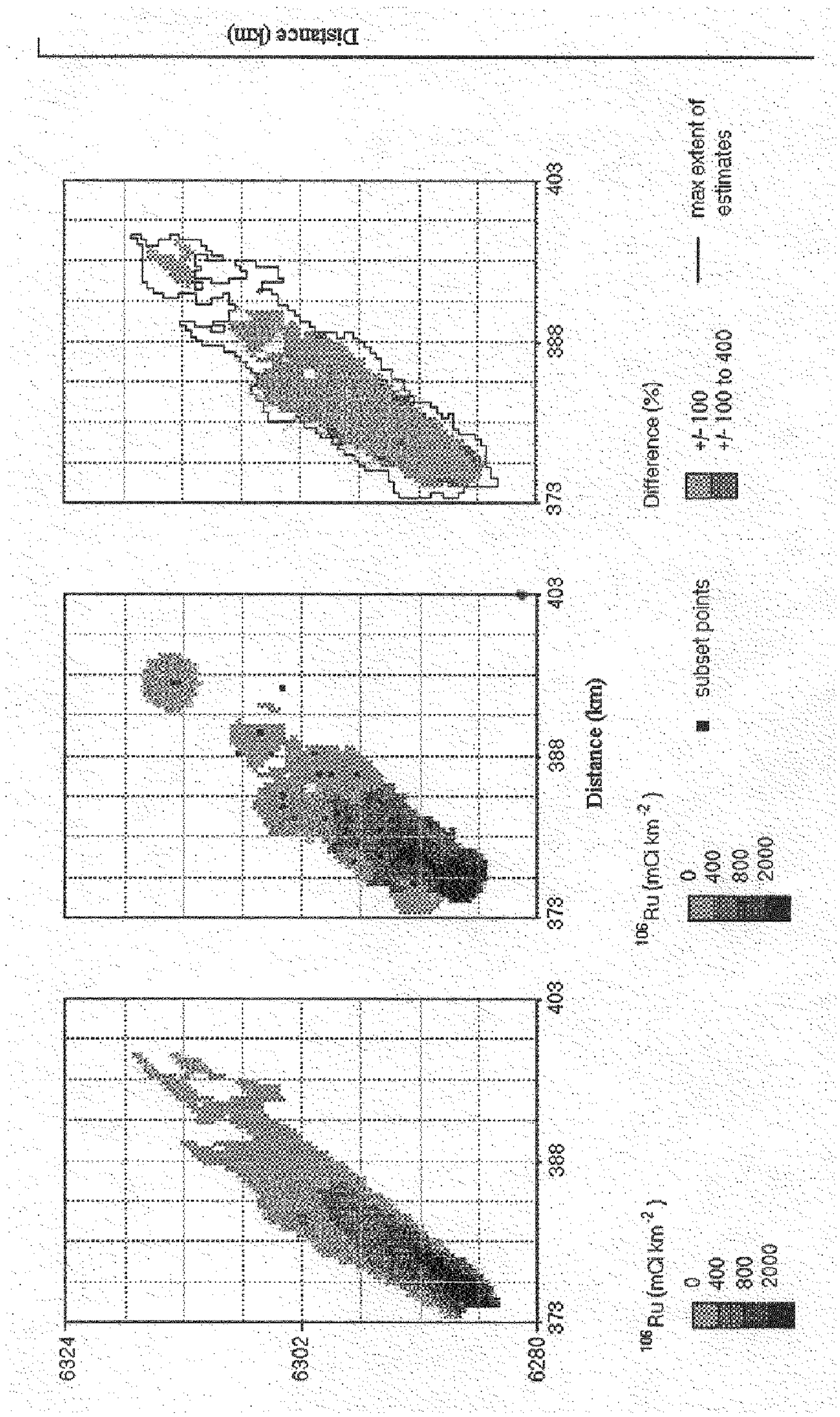

Figure 1 A comparison of an Ordinary Kriging estimate of 106Ru contamination from the Tomsk-7 accident using (700) measurements (left), a subset of 40 randomly selected measurements (centre) and showing the difference between the two estimates (right).