SENSITIVITY ANALYSIS IN RISK ASSESSMENT OF DRINKING WATER CHEMICAL POLLUTION CAUSED BY MILITARY ACTIVITIES

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Abstract: This paper presents the sensitivity analysis of environmental pollution risk assessment caused by military activities. Using the example of carcinogenic risk assessment of contaminated drinking water consumption, the role of sensitivity analysis for environmental decision-making is shown. Sensitivity analysis is a valuable tool in quantitative risk assessment by determining critical aspects and effects of variations.

Keywords: Quantitative risk assessment; Sensitivity analysis; Contaminated drinking water consumption.

1 INTRODUCTION

Military activities even during peacetime have a significant impact on the environment and lead to chemical pollution that affects human health for a long time, with a number of substances at low and ultra-low concentrations which do not carry toxic effects on man, but under certain conditions can cause cancer. Reliable methods are needed to determine the effects of chemicals on humans for making decisions on environmental protection measures.

Environmental risk analysis is an effective tool that integrates environmental data with management solutions [1]. Risk analysis consists of three phases: assessment, management and risk communication, where the risk assessment phase is the most important phase and consists of the following components [2]:

1. Identification of hazards - recording of all chemicals that pollute the environment to determine their toxicity to humans or ecosystems;
2. Evaluation of exposure - in general, purpose of exposure assessment is to characterize the mechanisms by which receptors are exposed to chemicals, and to quantify the magnitude of those exposures. This is also the assessment of received doses and the number of persons exposed to such exposure and for which it seems to be probable;
3. Evaluation of dependence "dose - response" - a search for numerical correlations that connect dose of substance with the prevalence of a particular adverse effect;
4. Risk characterization - includes evaluation of possible and real adverse effects to human health or the environment.

Risk assessment has some uncertainties on each stage of evaluation. The sources of uncertainties are:

1. During the identification of hazards - unidentified hazards, different results, quality and method of measurement in obtaining data, extrapolation of the results to the target population;
2. During the assessment of exposure - a conceptual model of contamination (a way of impact, distribution and transformation of pollutants in the environment, errors in determining and measuring the concentration of pollutants during field research), model of exposure (ways of getting contaminants into the body, determining the spatial and temporal boundaries), the determination of target population;
3. During the evaluation of dependence "dose - response" - errors in determining and measuring the concentration of pollutants in conducting epidemiological studies, interspecific and intraspecific differences in conducting toxicological studies, model of extrapolation from large to small doses of pollutants impact on the body;
4. While characterizing the risk the uncertainty of earlier stages has place.

In turn, the uncertainty can be divided into ignorance, i.e. the lack of knowledge about specific factors, parameters and models used in the analysis of risk, and variability, i.e. the inconstancy of parameters due to their natural heterogeneity [3]. If ignorance can be reduced by collecting additional data, increased measurement accuracy, improved models, etc., reduce the variability in this way is impossible.

In any case, the risk determination process can be represented as a specific model with input parameters at the output of which we obtain the desired risk value. In general, the uncertainty of risk is determined by the uncertainty of the input values and the sensitivity of the model (Fig. 1).

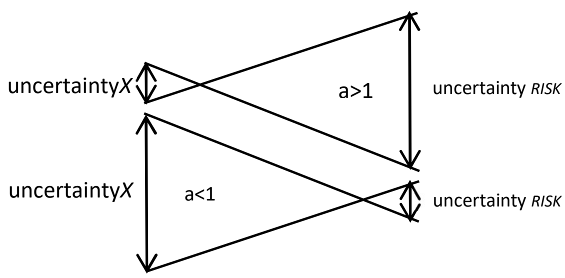

Fig. 1 Relationships between model sensitivity and risk uncertainty in a one-parameter model *RISK* = *aX* (*a* - model coefficient)
Source: author.

From Fig. 1 follows that in the bottom model, the predicted risk value is not as sensitive to the input values of X because the model sensitivity is lower, even though there is high uncertainty in the X. In the top model, risk is highly sensitive to even the small X uncertainty because of the high model sensitivity.

Sensitivity analysis is the assessment of the impact of changes in input values on model outputs. Sensitivity analysis of risk models can be used to identify the most significant exposure factors to aid in developing priorities for risk mitigation. Sensitivity analysis can be used as an aid in identifying the importance of uncertainties in the model for the purpose of prioritizing additional data collection or research. Sensitivity analysis can also be used to provide insight into the robustness of model results when making decisions [4].

Sensitivity analysis methods may be broadly classified as mathematical methods, statistical (or probabilistic) methods, and graphical methods. This classification helps in understanding applicability of sensitivity analysis methods for different types of models, and in selecting appropriate methods according to their usefulness to a decision-maker.

Mathematical methods are useful for deterministic and probabilistic models. Statistical methods are generally used for probabilistic models. Graphical methods are usually complimentary to mathematical and statistical methods. Graphical methods can be used for any kind of model [5].

Mathematical methods assess sensitivity of a model output to the range of variation of an input. These methods typically involve calculating the output for a few values of an input within the possible range. For example, the output of a model can be calculated for the highest and lowest possible values of an input. Sensitivity is usually described in terms of relative change in the output. These methods assess the impact of range of variation in the input values on the output [6]. Mathematical methods are helpful in screening the most important inputs. Mathematical methods can be used to identify inputs that require further data identification and research in the case of deterministic models.

Statistical methods involve running simulations in which inputs are assigned probability distributions and assessment of the effect of variance in inputs on the output distribution. Depending upon the method, one or more inputs are varied at a time. Statistical methods allow one to identify the effect of simultaneous interactions among multiple inputs. Distributions for model inputs can be propagated through the model using a variety of techniques, e.g. Monte Carlo simulation and other methods [4].

Graphical methods give representation of sensitivity in the form of graphs, charts, or surfaces. Generally, graphical methods are used to give a visual indication of how an output is affected by variation in inputs. Graphical methods can be used as a screening method before further analysis of a model or to represent complex dependencies between inputs and outputs. Graphical methods can be used to complement the results of mathematical and statistical methods for better interpretation [7].

Methods for sensitivity analysis, their advantages and disadvantages are discussed in more details in [4,5,7].

The importance of the probabilistic assessment of the risk of chemical contamination for the exposure of people caused by military actions is considered elsewhere, for example, [8,9]. Probabilistic risk assessment uses probability distributions instead of point values to calculate the risk, getting to ultimately probabilistic distribution of risk values. In this case, you can get the value of the probability of exceeding the level of risk that is of interest, namely, to quantify the value of uncertainty, what cannot be done using deterministic values. Thus probabilistic risk assessment provides with unique and important additional information that is used for optimal risk management.

To assess the sensitivity in this case, statistical methods are the most preferred. In [5,7] discussed such statistical methods for sensitivity analysis, including linear regression analysis (RA), analysis of variance (ANOVA), response surface method (RSM), Fourier Amplitude Sensitivity Test (FAST), Mutual Information Index (MII), Categorical and Regression Trees (CART) and Sobol's method, their advantages and disadvantages were discussed also.

The analysis carried out in the [5,7] indicates that to some extent all statistical methods are suitable for assessing the sensitivity of ecological risk models. Some methods are easier to apply in practice than others. The ease of application may often constrain the feasibility of a method. A method is typically easier to implement when software tools already exist, especially if they have user-friendly interfaces. Of course, ease of implementation will be a function of software availability and programming skill level [7].

The objective of this work is, using available software, to demonstrate the importance and usefulness of sensitivity analysis in risk assessment of chemical pollution caused by military activities.

2 CASE STUDY

The materials of paper [10], which analyses the environment condition after the accident on ammunition depot in Novobohdanivka, Zaporozhye region, Ukraine that happened on 6 – 15 of May 2004, are the basis for the research.

After the accident, river Molochna, which was widely used by citizens of Troitske village as the only source of drinking water was contaminated by some chemicals that changed its composition. The risk assessment was performed in stages (by tiers), from simple (deterministic) to more complex (using the one-dimensional and later two-dimensional Monte-Carlo method). Studies have shown that water is not suitable for drinking and environmental measures are necessary.

In order to make an informed decision that is optimal in terms of financial costs, it is important to know the components that affect the water consumption of the population. In this sense, conducting a sensitivity analysis of an appropriate water consumption risk model will be very useful.

In order to evaluate possible uncertainties a probabilistic risk assessment was performed [10]. This gives possibility to use statistical methods for analyzing the sensitivity of a risk model and determine the most important components affecting the risk value.

Risk models are represented by the following equations.

Carcinogenic risk:

$$CR = \sum_{i=1}^{N_R} ICR_i, \quad (1)$$

CR – is the value of full individual cancer risk caused by the action of N_R carcinogens;

ICR – is the value of individual cancer risk caused by the action of *i*-carcinogen;

N_R – is the total amount of carcinogens.

$$ICR = ADD \cdot SF, \quad (2)$$

ADD – is an average daily dose of chemicals consumed by the recipient;

SF – is a slope factor for the particular substance, which characterizes the degree of increase of cancer risk with increasing of the dose per unit.

Non-carcinogenic risk is defined by hazard index *HI*:

$$HI = \sum_{j=1}^{N} HQ_j, \quad (3)$$

HQ – is the hazard coefficient of j-substance;

N – is the total amount of hazardous substances.

$$HQ = ADD/RfD, \quad (4)$$

ADD – the average daily dose of a chemical substance;

RfD – reference dose, quantity that characterizes the daily effect of a substance during lifetime and, probably does not result in appearance of an unacceptable risk to the health of sensitive groups.

$$ADD = C_W \cdot IR_W, \quad (5)$$

C_W – is the concentration of the chemical substance in water;

IR_W – rationed per human unit mass volume of drinking water consumed by a person per day.

According to [11] IR_W is determined by log-normal distribution with the parameters given in Tab. 1.

Tab. 1 Parameters for lognormal distribution of drinking water, consumed by a person per day (IR_W), ml / (kg · day).

Age group, years	Average value of natural logarithm IR_W	Standard deviation of natural logarithm IR_W
1-3	3.49	0.75
4-6	3.33	0.68
7-10	2.97	0.68
11-14	2.66	0.71
15-19	2.43	0.74
20-44	2.61	0.68
45-64	2.92	0.52
65-74	2.92	0.49
75+	2.88	0.50

Source: author.

Tab. 2 Concentration of soluble forms of inorganic compounds in surface waters of the Molochna River

Parameter	Cu	Mn	Zn	Cd	Pb	Cr	Ni	Fe
Ion concentration in water, mg/l	9,5±0,9	0,414±0,004	0,97±0,1	0,021±0,001	0,62±0,4	0,239±0,002	1,06±0,06	11,6±0,3

Source: author.

In the first approximation, we take the form of distribution of chemical pollution concentrations in river water as normal (Tab. 2).

Risk modeling and sensitivity analysis was performed using a spreadsheet Excel® with add-in Crystal Ball® software. Crystal Ball calculates sensitivity by computing Spearman rank correlation coefficients between every input and every output values while the simulation is running. Correlation coefficients provide a meaningful measure of the degree to which inputs and outputs change together. If this values have a high correlation coefficient, it means that the inputs has a significant impact on the outputs. Correlation coefficients can range from -1 to +1. The value of -1 represents a perfect negative correlation while a value of +1 represents a perfect positive correlation. A value of zero represents a lack of correlation. Positive coefficients indicate that an increase in the inputs is associated with an increase in the outputs. Negative coefficients imply the opposite situation. The larger the absolute value of the correlation coefficient, the stronger the relationship.

Method disadvantages: correlation does not imply causation; there can be a case where a third variable is influencing the two variables with high correlation; Spearman coefficients are inaccurate for non-monotonic models.

The strength of the relationship between inputs (x) and outputs (y) (Contribution To Variance) in Crystal Ball expressed by squaring the correlation coefficient and multiplying by 100. For example, a correlation of 0.5 means 25 % of the variance in (y) is "explained" or predicted by the (x) variable.

Tab. 3 shows the results of sensitivity analysis of carcinogenic risk significance from input values: drinking water consumption and concentrations and properties of carcinogens in it for children and adults.

Tab. 3 Results of carcinogenic risk sensitivity analysis

Values	Contribution to Variance, %	Rank Correlation
Children		
IR_W (age 1-3)	49,29	0,49
IR_W (age 4-6)	48,08	0,48
C_{Ni}	2,52	0,11
C_{Cr+VI}	0,10	0,02
C_{Pb}	5,04E-05	0,00
C_{Cd}	1,06E-06	0,00
Adults		
IR_W (age 15-19)	17,82	0,20
IR_W (age 20-44)	20,54	0,21
IR_W (age 45-64)	17,34	0,19
IR_W (age 65-74)	15,80	0,18
IR_W (age 75+)	14,35	0,18
C_{Ni}	14,04	0,17
C_{Cr+VI}	0,071	0,01
C_{Pb}	0,017	0,006
C_{Cd}	0,016	0,006

Source: author.

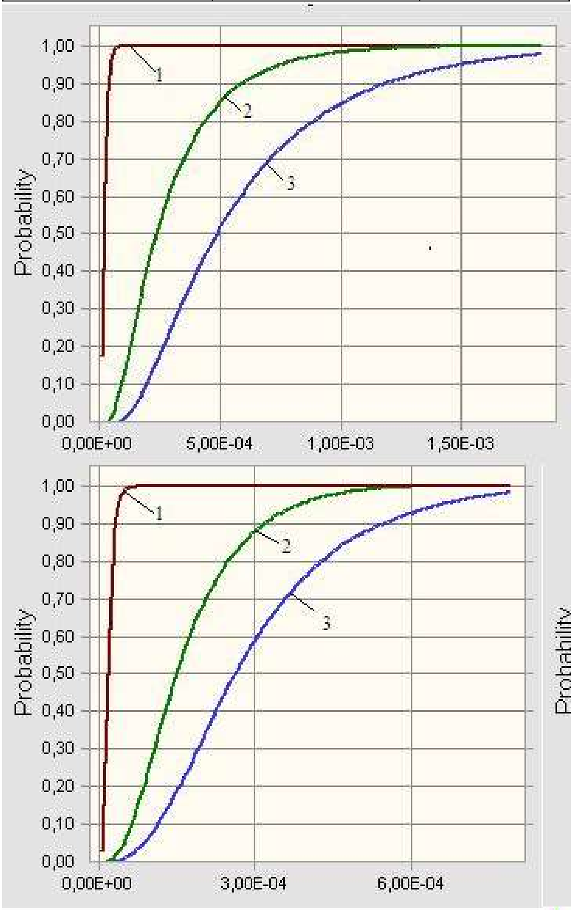

Fig. 2 Cumulative distribution function of carcinogenic risk from polluted water consumption: upper figure - children; lower - adults; 1 - halved consumption of polluted water; 2 - halved concentration of carcinogens; 3 - real water consumption

Source: author.

Tab. 4 Distributions statistical data

Statistic	Children			Adults		
Distributions	(1)	(2)	(3)	(1)	(2)	(3)
Trials	10 000	10 000	10 000	10 000	10 000	10 000
Mean	2,78E-05	3,07E-04	6,14E-04	2,24E-05	1,74E-04	3,00E-04
Median	2,55E-05	2,41E-04	4,90E-04	2,09E-05	1,50E-04	2,62E-04
Standard Deviation	1,19E-05	2,30E-04	4,42E-04	9,99E-06	1,05E-04	1,75E-04
Variance	1,42E-10	5,28E-08	1,95E-07	9,98E-11	1,09E-08	3,06E-08
Skewness	1,44	1,88	1,75	1,38	1,34	1,24
Kurtosis	7,18	7,60	6,95	7,72	5,26	4,8
Coeff. of Variability	0,43	0,74	0,71971	0,45	0,60	0,58
Minimum	5,08E-06	2,03E-05	7,62E-05	2,98E-06	1,47E-05	2,98E-05
Maximum	1,50E-04	1,83E-03	3,51E-03	1,25E-04	7,76E-04	1,20E-03
Mean Std. Error	1,19E-07	2,30E-06	4,42E-06	9,99E-08	1,05E-06	1,75E-06

Source: author.

An important conclusion can be drawn from the sensitivity analysis. The value of carcinogenic risk is mainly influenced by amount of consumed water (IR_W). The concentration of carcinogens, with the exception of nickel, plays a minor role. This is confirmed by model risk calculations with a halved consumption of polluted water and a halved concentration of carcinogens (Fig. 2). Table 4 shows the statistical data of the distributions.

It follows from the above data that reducing the consumption of polluted water by half, for example, while providing the population with clean imported water, reduces the risk of cancer to almost acceptable limits. Reducing the concentration of pollutants by half does not provide a sufficient reduction in the level of risk.

Ultimately, the way to reduce carcinogenic risk is determined by a feasibility study. However, sensitivity analysis in risk assessment provides additional opportunities for choosing the optimal decision to reduce risk.

3 CONCLUSION

Many different factors impact on extend to which a chemical pollution poses a risk to consumers of drinking water and some of these factors are more important than others. Therefore, it is important to focus risk assessment initially on the main factors. For this purpose one should start with sensitivity analysis.

Such an analysis will give insight to the important processes and phenomena and will show main-determining steps and relevant aspects. They can be helpful to determine hazards, determine main phenomena quantitatively important for risk, calculate the effect of changes in the process, and enable a wide range of operating strategies to be evaluated. The results can be used as the basis for decisions and to determine which stages or processes require more detailed analysis.

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