Environmental Threat Calculation Dealing with the Risk of Industrial Atmospheric Emission

A. Baklanov(✉), T. Dmitrieva, K. Tulendenova, A. Bugubayeva, and M. Rakhimberdinova

D. Serikbaev East Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan
abaklanov@ektu.kz

Abstract. The following work proposes an estimation procedure of risks based on the calculation modeling action of concentration of the environmental exposure thrown into atmosphere by industrial enterprises with consideration for atmosphere perseverance category and wind rose in the region. The information system of risk assessment employing the suggested mathematical model for computation of environmental hazards is described in the article.

The information system has client/server architecture and uses OLAP technology to get the necessary information. The received data on Ust-Kamenogorsk allowed the authors to analyze the weighting risk coefficient effect on per unit value of environmental threat. The calculation is performed for the city of Ust-Kamenogorsk.

Keywords: Ecology · Risks · Damage · Emissions · Air pollution

1 Introduction

On December 12 2015 the Paris Climate Agreement was accepted. 195 forum participants decided to not let the planet average temperature increase more than 2° by 2100 in comparison with the pre-industrial era. However, the document does not provide for quantitative obligations of reducing or limiting CO2 emissions [1].

Kazakhstan announced its intentions to reduce emissions by 15% and conditionally by 25% with additional international support by 2030 from the base year of 1990 [2]. The set goals can contribute to the low-carbon "green" development path.

The main sources of environment pollution and degradation of natural systems are industry, agriculture, motor vehicles and other anthropogenic factors. Of all the constituent components of the biosphere and the environment, the atmosphere is the most sensitive. It is the first to receive polluting substances not only in gaseous, but also liquid and solid state.

Y. Shokin and Z. Shaimardanov (Eds.): CITech 2018, CCIS 998, pp. 23–33, 2019.
https://doi.org/10.1007/978-3-030-12203-4_3

Man pollutes the atmosphere for thousands of years, however the consequences of the use of fire, which he has used all this period were not significant. What is the atmosphere? The air around us is a mixture of gases or, in other words, the atmosphere enveloping our globe. The afflux of various pollutants into the atmosphere from stationary industrial sources makes currently more than 4 million tons per year.

A significant amount of highly toxic gaseous and solid substances is released into the atmosphere over Kazakhstan. If we compare the number of emissions from various stationary sources, about 50% is emitted by heat and power sources and 33% by mining and non-ferrous metallurgy enterprises. The largest number of emissions of various pollutants takes place in East Kazakhstan-2231.4 thousand tons/year, which males 43% of the total emissions around Kazakhstan.

The second place in the number of emissions belongs to Central Kazakhstan-1868 thousand tons/year or 36%. The least polluted is the atmosphere in Northern Kazakhstan: 363.2 thousand tons/year (7%) and Southern Kazakhstan: 415.1 thousand tons/year, which amounts to 8%. The most mobile, with a wide range of action, are oxides of nitrogen and sulfur. They cover considerable distances and have a strong impact on destruction of crops in the first place.

A significant contribution to the pollution of the air basin and other environmental components is made by motor vehicles of the Republic. Their emissions, especially in urban areas, range from 25 to 50%. According to the pollution of the atmosphere with motor exhaust gases in the first place is Almaty - 75%, then Aktobe - 47.1, Semey 46.6, Zhambyl - 43.1, and Ust-Kamenogorsk - 41.4%. Zhezkazgan has the least content of exhaust gas in the atmosphere - 14.8. Then go Petropavlovsk - 26.3 and Ridder - 27.6%. However, the highest pollutant gas content of the atmospheric air, oddly enough was established in the cities such as Kostanay - 84.7% and Uralsk - 81.7%, where the number of industrial enterprises and vehicles is relatively fewer than in the above-mentioned cities. Motor vehicles are the main pollutants of air and, to a certain extent, of soil and water. According to statistics, there are more than 200 thousand cars per more than a million Almaty population-today.

Pollution of the atmosphere of cities with solid and gaseous pollutants reduces the intensity of sunlight, clogs the air with a significant amount of solid particles, which serve as concentration nuclei, contributing to the emergence of fogs and smogs. The high content of harmful impurities in the atmosphere in the solid and gaseous state affects the thermal properties of the atmosphere. Under the influence of sunlight, as a result of photochemical reactions, a summation effect is formed, thus contributing to the emergence of new, more toxic substances that cause smog.

2 Mathematical Model

The environmental hazard is determined by two factors for the population living in a territory with a high industrial content: damage from actual danger and risk (potential hazard) in the event of emergency situations. For this reason the environmental hazard value in relative terms can be presented in the form [3]:

$$G_{RT} = \phi(Y_{RT}, R_{RT}), \tag{1}$$

where G_{RT} – environmental hazard risk in relative terms; Y_{RT} – damage in dimensionless relative terms; R_{RT} – risk in dimensionless relative terms.

The conditions determined by physical laws can be written in the following form:

$$\frac{d\phi}{dY_{RT}} > 0; \frac{d\phi}{dR_{RT}} > 0; \phi(0, R_{RT} > 0); \phi(Y_{RT} > 0, 0); \phi(0, 0) = 0. \tag{2}$$

A similar approach to risk calculation was used in the articles [4,5]. The damage and risk characteristics independence requires the ϕ function presentation in their product form. Considering the conditions 2 the proposed ϕ function form in [3] allows us to write the environmental risk value in the following form:

$$G_{RT} = (Y_{RT} + 1)^{P_Y} \cdot (R_{RT} + 1)^{P_R} - 1. \tag{3}$$

where P_Y and P_R – weighted coefficients which are describe the damage and risk fractional contribution to the environmental hazards value.

According to the model proposed in [3], the damage to the Y_{RT} population consists of two components: direct damage to Y_{DD} immediately inflicted to the population and indirect damage Y_{IND} caused to the population due to habitat degradation:

$$Y_{RT} = (Y_{DD} + 1)^{P_{YDD}} \cdot (Y_{IND} + 1)^{P_{RIND}} - 1. \tag{4}$$

The specific weight coefficients choice of direct P_{YDD} and indirect P_{RIND} damages depends on the natural environment efficiency on the vital activity of the population living in the given territory. In the case of a natural environment marked impact on human living conditions the equivalent factors model can be accepted, where the weight coefficients are equal and have value 0.5. Must be chosen the selected factors model and particularly accept in the case of a natural environment weak impact on human living conditions:

$$P_{YDD} : P_{RIND} = 9 : 1. \tag{5}$$

Considering the industrial emissions impact in the atmosphere we have [3] the following expressions for Y_{DD} and Y_{IND}:

$$Y_{DD} = \sum_{i=1}^{n} \frac{C_i^{emis}}{MPC_i^{emis}} \cdot \frac{N_{ter}}{N_{cntr}}, \tag{6}$$

$$Y_{IND} = \sum_{i=1}^{n} \frac{C_i^{emis}}{MPC_i^{emis}} \cdot \frac{S_{ter}}{S_{reg}} \cdot \beta. \tag{7}$$

where C_i^{emis} – given territory actual (measured) concentration in the atmosphere of the i-th substance;

MPC_i^{emis} – maximum allowable concentration of the i-th substance in the air;

N_{ter} – population density living on the polluted territory under consideration;

N_{cntr} – country average population density;

S_{ter} – polluted atmosphere area;

S_{reg} – ecologically homogeneous region area that includes given territory;

β – given territory significance index in conserving the natural environment in the region ($0 \le \beta \le 1$).

Expressions 4–7 are allowed to calculate $Y O \Pi$ - damage in dimensionless relative terms. The general expression that allows estimating the damage numerically appears as follow:

$$Y_{RT} = \left(\sum_{i=1}^{n} \frac{C_i^{emis}}{MPC_i^{emis}} \cdot \frac{N_{ter}}{N_{cntr}} + 1\right)^{0.9} \cdot \left(\sum_{i=1}^{n} \frac{C_i^{emis}}{MPC_i^{emis}} \cdot \frac{S_{ter}}{S_{reg}} \cdot \beta + 1\right)^{0.1} - 1. \quad (8)$$

Similarly, R_{RT} is calculated in dimensionless relative indicators:

$$R_{RT} = \left(\sum_{i=1}^{n} \frac{C_i^{emis}}{MPC_i^{emis}} \cdot \frac{N_{ter}}{N_{cntr}} + 1\right)^{0.9} \cdot \left(\sum_{i=1}^{n} \frac{C_i^{emis}}{MPC_i^{emis}} \cdot \frac{S_{ter}}{S_{reg}} \cdot \beta + 1\right)^{0.1} - 1. \quad (9)$$

The damage and risk weight coefficients can be calculated using formulas that express the relative cost parameters contribution of damage and risk in the environmental hazard total cost:

$$P_Y = \frac{Y_{VT}}{G_{VT}}; P_R = \frac{R_{VT}}{G_{VT}}. \quad (10)$$

where Y_{VT} – general integrated damage to the territory in value term;

R_{VT} – risk cost parameters;

G_{VT} – environmental hazard total cost $Y_{VT} + R_{VT}$.

The following expressions are used based on the proposed damage and risk presentation in value terms:

$$Y_{VT} = Y_{NORM} + Y_{POP}. \quad (11)$$

where Y_{NORM} – damage cost from the environment (normatively determined damage) direct pollution;

Y_{POP} – social and ecological damage cost due to deteriorating the population living conditions.

Expression 11 can be written in the following form:

$$Y_{VT} = a \cdot \sigma \cdot f \cdot M_{COND} + Y_G + Y_Q + Y_W. \quad (12)$$

where a – proportionality cost factor for the conditional air contaminant (tg/cond.t);

σ – dimensionless coefficient, which considers the territory peculiarities;

f – dimensionless coefficient that considers the contaminant fractions size, the dispersal pattern, and the subsidence rate in the atmosphere;

M_{COND} – annual release reduced mass in the atmosphere from conditional polluter (taking into account its ecological danger) (cond.t./year);

Y_G – reduced annual damage, which is connected with decreasing population growth rate parameter;

Y_Q – reduced annual damage that is connected with decreasing living standards indicator, which is defined by the size of average life duration;

Y_W – reduced annual damage that is connected with decreasing population employ ability indicator.

The following expressions can be used for M_{COND}, Y_G, Y_Q and Y_W:

$$M_{COND} = \sum_{i=1}^{n} \frac{A_i}{m_i}, \quad (13)$$

where m_i – annual emission mass of the i-th admixture to the atmosphere (t/year); A_i – relative aggressiveness dimensionless parameter of the i-th admixture (cond.t/year).

$$Y_G = \left(\frac{\Delta N_{repr}^{cntr}}{N_{repr}^{cntr}} - \frac{\Delta N_{repr}^{ter}}{N_{repr}^{ter}}\right) \cdot N_{repr}^{ter} \cdot q_{repr}^{cntr}, \quad (14)$$

where ΔN_{repr}^{cntr} – reproductive age country population annual increase from 16 to 60;

N_{repr}^{cntr} – reproductive age country population at the target year beginning;

ΔN_{repr}^{ter} – reproductive age annual population growth;

N_{repr}^{ter} – reproductive age territory population at the target year beginning;

q_{repr}^{cntr} – specific gross national product, per head the country's reproductive population (tenge/person).

$$Y_Q = N_{repr}^{ter} \cdot q_{repr}^{cntr} \cdot \left(T_L^{cntr} - \frac{T_L^{ter}}{T_L^{cntr}}\right), \quad (15)$$

where T_L^{cntr} – average life duration in a country;

T_L^{ter} – average life duration in a territory.

$$Y_W = N_{repr}^{ter} \cdot q_{repr}^{cntr} \cdot (n_{repr}^{cntr} - n_{repr}^{ter}), \quad (16)$$

where n_{repr}^{cntr} – average annual number of man-days per reproductive age person in a country;

n_{repr}^{ter} – average annual number of man-days per reproductive age person in a territory.

The cost risk index is expressed as follows:

$$R_{VT} = Y_{norm} \cdot (\frac{M_{cond}^{AE}}{M_{cond}^{norm}}), \tag{17}$$

where M_{cond}^{AE} – possible amount of accidental emissions;
Y_{norm} and M_{cond}^{norm} – damage cost and the pollutant quantity in normative evaluation by the standard methodology.

The obtained general expression can allow to model and study the causes of changes in geoecological risks depending on all factors. This expression describes the environmental hazard value in relative terms; however the actually measured emissions concentrations data of harmful substances in the atmosphere are required for providing calculations. That is why calculation can be accomplished by analyzing the fact that damage has already occurred. Risk situations forecasting is impossible during the industrial plants performance using formula 8–17 because of the absence of C_i^{emis} values. The way out can be done by using theoretical formulas for calculating concentrations from an industrial plant's emissions stationary source. Then we can find an expression for the particular plant considering the air condition of a certain region [6], which can be substituted in place of C_i^{emis}.

The mathematical expression for the concentration from a point source with a constant power – Q (kg/s) for Ust-Kamenogorsk can be written as:

$$C(x, y, z, t) = \frac{f(A) \cdot Q}{2\pi\sigma_y\sigma_z U} \cdot \exp(-\frac{y^2}{2\sigma_y^2}) \cdot [\exp(-\frac{z - H^2}{2\sigma_z^2}) + \exp(-\frac{z + H^2}{2\sigma_z^2})], \tag{18}$$

where Q – source power (kg/s);
σ_y and σ_z – dispersion parameters that depend on the atmosphere stability and the distance from the source "x" (m);
U – wind speed (m/s);
H – source height (m);
x, y, z – axial, transverse and vertical coordinates;
f(A) – impurity fraction in the mixing layer ("A"– mixing layer height).

The dispersion parameters σ_y yand σ_z were calculated by the formulas that were obtained by approximating the data for various atmospheric stability categories.

The calculating average annual concentrations problem solution in the residential zone of Ust-Kamenogorsk comes to the integration of all possible pollutants concentrations in a given point in space (x, y) and emission sources. Since it is assumed that within the M-rumba wind rose sector, the wind direction is fairly spread, which is typical for Ust-Kamenogorsk, the average annual concentration C (x, y) is calculated by the formula:

$$C(r, \theta) = \sum_{i=1}^{L} P_{V\,i} \cdot \left\{ \sum_{k=1}^{6} (P_k(U_i) \cdot \frac{M \cdot Q \cdot \gamma(x/U)}{2 \cdot \sqrt{2} \cdot \pi^{3/2} \cdot r \cdot U_i \cdot \sigma_z} \cdot f(A, H, \sigma_z)) \right\}, \tag{19}$$

where Q – source power (kg/s);

P_{Vi} – wind realization probability at speed U_i (m/s) in the corresponding M-rumbling scheme sector;

$P_k(U_i)$ – realization probability of atmosphere stability certain class with the wind U_i (A-1, B-2, ..., F-6);

θ – wind direction in polar coordinates;

r – distance from the pollution source to the point (x, y);

σ_z – vertical dispersion characteristic;

$f(A, H, \sigma_z))$ – influence function of the pollution source height (H) and the mixing layer height (A);

$M/2\pi$ – sector angular fraction in the winds M-pattern;

$\gamma(x/U) = \gamma(t)$ – concentration change function along the plume axis due to photochemical reactions, dry and wet deposition, etc. in time.

Substituting the expression 19 in 8–17 as C_i^{emis}, and the expression 18 as C_i^{emisAE}, we will get an expression allowing to analyze the existing atmospheric pollution risk situation from an industrial plant, and to identify factors that have a greater contribution for certain plant features.

3 Practical Implementation

To study the risk impact on the environmental hazards value in the region, we developed the informational system for risk assessment using the above model, considering numerical calculations that are modeling the harmful substances concentration behavior. Which are trapped in the atmosphere as a result of industrial plant emissions taking into account the atmospheric stability and wind rose category in the region.

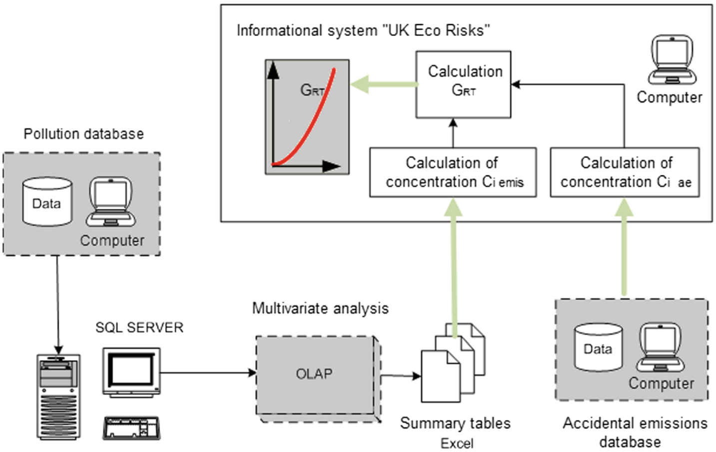

Fig. 1. General scheme of the informational system "UK Eco Risks".

The general scheme of the informational system “Ust-Kamenogorsk ecological risks” is presented in Fig. 1. The data from the atmospheric pollution database came to the SQL server, where the multidimensional cubes were built using OLAP technology and summary spreadsheets were created by slice and dice with the necessary information for us about the substances concentration upon which further calculation was continued. Information on emergency emissions came from the independent database in the separate informational system module. The quantitative analysis and the environmental hazard calculation were carried out in the region based on the incoming data.

4 Results

We analyzed the weight risk factor influence on the environmental hazard value in relative units based on the available data for Ust-Kamenogorsk [7].

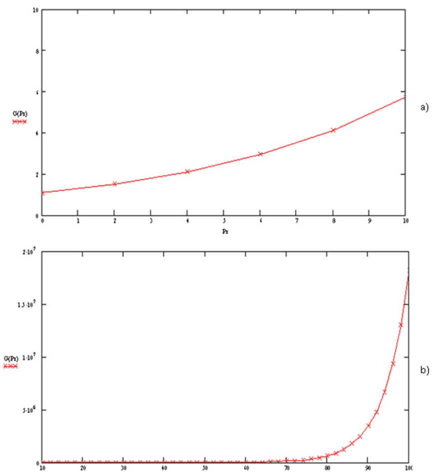

Fig. 2. Graphs of the environmental hazard value dependence on the environmental risk value.

Figure 2 shows the dependence of $G_{RT}(P_R)$. The important result is the P_R area identification, where the risk factor strong impact is manifested on the environmental hazards value. So, with the value of 70–100, we can observe the increase in environmental hazard from a low level (Fig. 2a) - 1–10 conventional units (Fig. 2b) to 106–107conventional units. Here with further studies on the probability of such events allow predicting the high ecological danger occurrence probability and, therefore, preventing this situation.

In addition using the formulas 18, 19 and data on a specific industrial plant, it is possible to determine the risks without providing quantitative measurements of pollutants in the studied region territory. Also the obtained information makes it possible to predict the ecological hazard occurrence that can lead to irreversible geoecological changes.

The most famous emergency situation that created unfavorable environmental conditions and entailed a significant increase in environmental danger appeared in the region in 1990, when, after the accident at the Ulba Metallurgical Plant, the beryllium cloud spread hundreds of kilometers and reached the territory of China (these emissions are the most significant for all history of Kazakhstan and world practice).

The pattern of the distribution of the emergency release plume is presented in Fig. 3 The dotted line indicates the area of beryllium detection, which is approximately 12 thousand square kilometers.

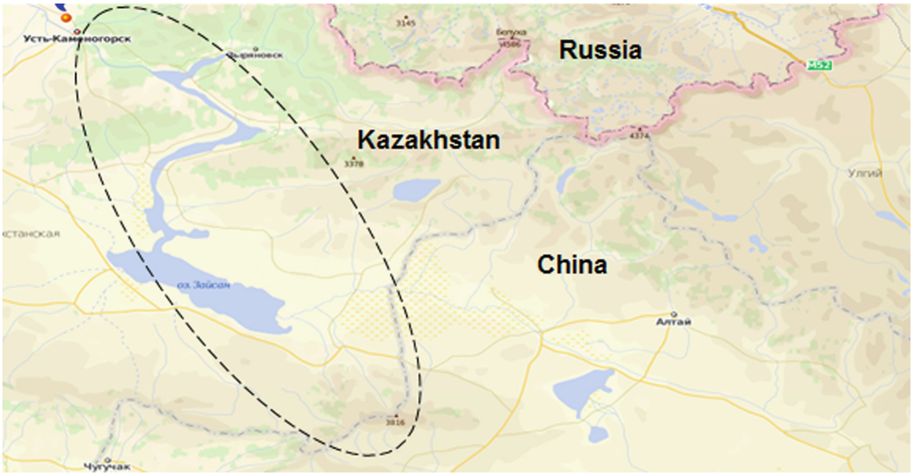

Fig. 3. Emission spread area.

In general, the magnitude of the environmental hazard depends on a large number of parameters; therefore, highlighting the influence of the risk factor will make it possible to realistically assess the possible impact of existing industrial enterprises, as well as being built or designed, on the appearance of environmental hazard in the region and the extent of possible violations associated with risk.

Having information about the size of the consequences, we solved the inverse problem of estimating the value of the proportionality coefficient (by the area of the gas cloud propagation, calculated the emission power), and carried out calculations of the environmental risk. The values obtained for the 1990 JSC UMP accidental release are shown in Fig. 4 by dashed lines.

Thus, the calculated value of environmental risk in relative conditional units is 972 units and shows that the values calculated on real data are in the zone of a large growth gradient of the indicator of environmental hazard and are

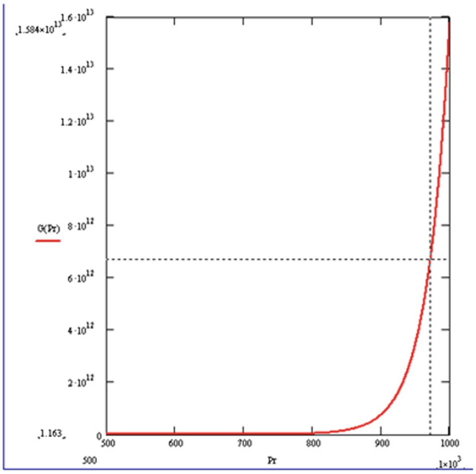

Fig. 4. The obtained values of P_R for the accidental release of 1990 JSC UMP.

$6,79 * 10^{12}$ in relative conditional units. In reality, this value shows that with emergency emissions of this magnitude, the environmental situation in the region deteriorates millions of times, since with a normally operating enterprise, the risks have indicators equal to $10^2 - 10^3$ in relative units.

5 Conclusion

In general, the environmental hazard value depends on the parameters large number, for this reason identifying the risk factor impact will allow us to assess the possible impact of existing (designed) industrial plants on the environmental hazards occurrence in the region, and to predict the possible violations extent associated with risk.

Conclusions and recommendations can be widely used in cities prone to the negative effects of industrial emissions. A new approach to estimating the risks of emissions from industrial enterprises and their impact on the magnitude of damages is proposed. The program complex and the information system make it possible to develop practical recommendations and evaluate the effectiveness of environmental protection measures in a new way.

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