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ECOLOGICAL RISKS RELATED TO ACCIDENTS AT PULP AND PAPER PLANTS: THE CASE OF THE MANTUROVO PULP AND PAPER PLANT PROJECT

ABSTRACT. The paper presents approaches to quantitative and spatial assessment of emergency environmental risks at new sites of pulp and paper production using mathematical statistics, probability theory, and cartographic modeling. Damage assessment is based on the type and sphere (atmosphere, soil, and underground and surface waters) of impact. Although damage assessment considers governmentally approved methodology, the formula suggested for the assessment contains some suitable improvements. In addition, a brief characterization of technological process at pulp and paper plants provides objective substantiation of possible accident scenarios. Conclusions discuss economic and social benefits of pulp and paper plants versus their ecological disadvantages.

KEY WORDS: environmental risks, pulp and paper industry

INTRODUCTION

Recently, increasing attention is paid to issues related to the ascending impact of different hazardous industrial facilities and transport, as a rule, characterized by "technological risk" or "threat of an emergency or emergency situation". Risk is an expected assessment of an adverse event's probability; this indicator includes the possibility of adverse consequences of any act or course of events, which is measured by the probability of such effects or likely magnitude of losses. There is a need to consider ecological (environmental) conditions and the natural potential of the territory in the integrated index of technological risk for the most comprehensive description of economic structures' dangers. Not all approaches to risk assessment meet the objectives of ensuring complex security because of significant complexity of technological and natural process and uncertainty of emergency scenarios, which is influenced by numerous factors.

It is necessary to consider environmental risks, i.e., anthropogenic hazards for the environment. Such assessments are especially important at the stage of new industrial facilities planning, so one can choose the best location for construction that meets not only the resource requirements, but is also resistant to anthropogenic pollution.

The goal of this work was to define methodological approaches to ecological risk assessment for hazards associated with emergency release of liquid contaminants using Manturovo Pulp and Paper Plant (P&PP) (Kostroma region) as a case study. The P&PP was designed to be the largest in the European part of Russia with a capacity of 800 000 tons of pulp and 500 000 tons of paper per year.

To implement a comprehensive assessment of ecological risk, the following problems have to be solved:

- provide characteristics to pulp and paper industry as a source of environmental risk;

- assess the likelihood and consequences of emergencies at industrial facilities (to assess emergency risks);
- identify the areas of negative impact and zones most vulnerable to pollution.

METHODOLOGY

Prior to discussing methods of risk assessment, it is necessary to give the definition to the term "risk". "Risk is a measure of hazard, which is characterized by probability and amount of damage". From a mathematical point of view, risk is a mathematical expectance of damages for a considerate period and a product of emergency probability and damage [Akimov et al, 2001]:

$M(D) = Q\tau \cdot D$, where D is damage caused by disaster; $Q\tau$ is probability of its occurrence per year.

The probabilistic method is the most appropriate for risk of emergency situations assessment as it is completely transparent, objective, and is based on statistics of events that have taken place. This method is based on the use of mathematical models to determine the probabilities and consequences. Probability models vary in the level of detail, depending on the available data. The simplest model is based on the representation of the flow of emergencies as a Poisson stream of random events (in the theory of random processes, describes the amount of random events occurring with constant intensity). In this case, probability of occurrence per year is estimated by the formula:

$Q\tau = 1 - \exp(-\lambda\tau)$, where λ is intensity of emergency ($year^{-1}$). Intensity of emergency is determined by date on long-term observations, using the formula:

$\lambda = d/\Delta t$, where d is the number of emergencies over the observation period Δt. For very rare emergencies $Q\tau = \lambda\tau$.

For a more complete emergency risk assessment, one can use the formula:

$M(D) = \Sigma Q(\tau) \cdot D$, where D is the consequences of i-type emergency; $Q(\tau)$ is probability of i-type emergency over a period of time τ.

Damage in financial terms, in general, is estimated by the formula for each component of the geosystem:

$D = V \cdot H \cdot Kc$, where V is the volume (mass) of pollutants emitted (released) into the environment (defined as maximum possible); N is the National Standard Fee for release of 1 ton of pollutant [Russian Federation Government Resolution № 344 dated June 12, 2003]; Kc is a coefficient describing the ratio between pollutant concentrations and the maximum permissible concentrations (MPC) [SanR&N № 4630-88].

The method mentioned above is simple and allows avoiding complicated for prediction out-of-date coefficients that are used in official methodologies. In addition, there is a conversion factor, which depends on the ratio between after emergency pollutant concentrations and the MPC; the excess over the MPC is one of the main characteristics of the emergency hazard rate. To calculate after emergency concentrations of substances in the geosystem components, different techniques are used depending on the type of impact.

Accidents at pulp and paper plants are usually connected with liquid pollutant release. To assess damage, one can use the application of the official methodology, i.e., Recommendation to Action – RA 03-626-03 "Method for determining the size of harm that can be caused to the life or health of individuals, property of enterprises in a case of accidents at hydrotechnical structures". During emergency releases, three geosystem components are affected: soil and surface and underground waters (for simplicity, we will not consider the processes of pollutants entering the atmosphere through evaporation from the surface of water or soil). For each component of the environment, the concentration of pollutants is determined considering their background content. To estimate the parameters of pollution of soil and underground and surface waters with harmful substances, the following assumptions are recommended: the liquid phase infiltration in the area of impact through the soil is free, without damming from underground water; the water remaining in the soil-plant bed and in the natural hollows and depressions is not considered; and differentiation between pollution in the mass of soil, surface, and underground waters is not considered.

In determining the extent of soil contamination, it was assumed that the entire mass of pollutants filtered from the liquid remains in the soil layer and is spread evenly over the depth of the layer and the area of impact. In determining the extent of groundwater contamination, it has been suggested that the entire mass of pollutants filtered from the surface of the impact zone or from liquid storage gets into groundwater and is spread evenly in the groundwater flow over the area of impact. The calculation does not take into account retention of some harmful substances by the soil. In determining the parameters of contamination of surface water, it was assumed that the entire mass of harmful substances contained in the leaked or filtered liquid from the storage for water spreads evenly throughout the section.

Calculation of parameters of soil contamination. The volume of filtered liquid from the surface into the soil mass V_f (m^3) is defined as:

$V_f = K_f J F_f T_f$, where K_f is the filtration coefficient of the soil layer (m/day) determined based on the grain composition of the soil; J is the gradient of the infiltration flow; S_f is the filtration area (m^3)(equal to the area of impact); V_f should not exceed the total volume of fluid leaked from the storage.

Then, for each pollutant contained in the liquid waste, the concentration of harmful substances in the soil C_{si} (g/m^3) for the area of F_f is calculated:

$C_{si} = (C_i V_f / S_f\, Ms\, \rho s_d) + C_{sbi}$, where C_{si} is the concentration of *i*-pollutant in the liquid waste (mg/liter or g/m^3); Ms is the depth of the soil layer (m); ρ_{sd} is the density of the dry soil layer, (t/m^3); C_{sbi} is the background concentration of the *i*-substance in the soil (g/m^3).

Parameters Ms and ρ_{sd} are determined from surveys.

In the absence of specific input data, the following values are recommended for approximate estimates:

$$Ms = 0.5 - 1.0 \text{ m};$$

$$\rho_{sd} = 1.4 - 1.6 \text{ g/cm}^3.$$

Calculation of parameters of groundwater contamination. For each i-pollutant contained in the liquid waste, the concentration in groundwater C_{gwi} (g/m^3) for the impact zone is calculated as:

$C_{gwi} = (V_f C_i + S_f m_{gw} n_g C_{gwbi})/(V_f + S_f m_{gw} n_g)$, where C_{gwbi} is the background concentration of *i*-compound in groundwater; m_{gw} is the capacity of groundwater flow (m); and n_g is soil porosity.

Parameters are determined from survey.

Calculation of parameters of surface water contamination. In the case of a flowing water body (river), the concentration C_{wi} (g/m^3) will be:

$C_{wi} = (Q_{max} C_i + Q_w C_{wbi})/(Q_{max} + Q_w)$, where Q_{max} is the maximum flow rate from the storage (m^3/sec) and Q_w is the flow rate of the water body (m^3/sec).

In the case of Manturovo P&PP, we are dealing with a river, so the scenario with a closed water body will not be considered (this scenario may be found in the full version of RA 03-626-03). The resulting concentrations in the soil, groundwater, and surface water were compared with the MPC. Depending

Table 1. Values of the conversion factor *Kc*

Ratio between the final concentrations and the MPC	Pollution degree	Coefficient (*Kc*)
<2	Allowable	1
2–8	Low	1.2
8–16	Medium	1.4
16–32	High	1.6
>32	Very high	2.0

on the ratio between the final concentrations and the MPC, the conversion coefficient (*Kc*) has the following values (Table 1).

Spatial representation of environmental risks. The area of contaminated soil and underground water is calculated based on a simple model, where the zone is presented as a complex prism of a known volume (the volume of fluid that was released) and height (the minimal liquid layer). Thus, the area is equal to the quotient of the volume and the height.

In the case of an open hydrological object (river), the extent of affected area depends on many factors: the characteristics of the river (flow speed – V, the average depth at the site – h, and the water flow in the river – Q_1); the characteristics of runoff (harmful component, water flow – Q_2, the concentration of harmful component – C_i in wastewaters, and the background concentration – C_{bi}). The concentration of harmful components in the water at the place of the next intake is calculated by the formula:

$$C_{i1} = (C_i - C_{bi})/K,$$

where K is the dilution coefficient multiplicity;

$K = (\gamma Q_1 + Q_2)/Q_2$, where γ is the degree of wastewater completeness in the pond;

$$\gamma = (1 - \beta)/(Q_1 + Q_2)^{\beta},$$

$\beta = \exp(-\alpha L^{1/3})$, where L is the distance to the water intake; α is the coefficient taking into account hydrological factors of mixing;

$\alpha = \varepsilon(Lf/Ls) - (D/Q_2)^{1/2}$, where Lf/Ls is the coefficient of sinuosity of the river (for plain rivers on a short-range equals to 1); ε is the coefficient depending on the place of runoff release into the river; it equals to 1, if the release was at shore; D is the coefficient of turbulent diffusion; for plain rivers is determined by the formula:

$$D = hV/200.$$

PULP AND PAPER INDUSTRY AS A SOURCE OF ENVIRONMENTAL RISK

Current studies of pulp and paper industry (PPI) have a great potential due to the fact that this branch of national economy may soon become Russia's branch of specialization by virtue of rich resource potential [Kuzminov, 2009]. The main raw material for the Russian pulp and paper industry is wood. This is due to the rich forest resources and poorly established system of waste paper recycling. The most valuable type of wood is coniferous; its reserves in Russia are significantly higher than in other countries. Coniferous plant fibers are longer, allowing to produce higher quality types of paper and pulp, characterized, above all, by high solidity. But the use of birch and aspen has a great potential also. Modern technologies allow receiving products of considerably high quality out of deciduous wood.

Production of pulp and paper products includes the processes of chemical and mechanical wood processing, as well as secondary processes related to full or partial recovery of waste. The process of chemical treatment of wood is the dominant process that causes great harm to the environment [Kasparov, 1979].

The mass fraction of cellulose in wood varies from 32 to 56%. In softwood, the percentage of cellulose is usually 46–54%; in hardwood, it is 41–45%. In addition to cellulose, wood contains large amounts of hemicellulose

(20–35%) and lignin (18–28%). The main purpose of cellulose cooking is freeing wood from fibers, so its other name is delignification. Based on the chemical composition of the reactants in the process of cellulose cooking, one can define alkaline and acidic methods of cooking. Alkaline methods are the sulfate type of cooking dominant, at the present time, in Russia and the world. The main reagents used in the alkaline methods are sodium hydroxide and sodium sulfide. This method allows processing both hardwood and softwood and can operate with highly resinous wood.

Pulp is cooked with cooking liquor (sulphate, or white alkali liquor) containing sodium hydroxide, sodium sulfide, a small amount of carbonate and sodium sulphate. Sodium hydroxide and sodium sulfide are the active part of white liquor. Their total concentration, in terms of Na_2O, ranges from 70 to 120 g per liter.

A pulp mill digester processes about 450–500 tons of pulp per day. The upper zone of the digester is for brewing, the middle part is for cooking, and in the lower part, the pulp is washed with weak alkaline. The pulp mass with concentration of 14–16% and cooled to 80–85°C is continuously unloaded into the blow tank. Cooking processes take about 4.5 hours.

At the end, the cooking liquor (7–10 m^3 per a ton of pulp) becomes almost black, so it is called black alkali liquor. It collects most of the wood lignin in the form of alkali lignin and hemicelluloses portion, which, in alkaline medium, becomes hydrolyzed and oxidized to a form of oxy acids. Black alkali liquor is processed into green alkali liquor which is treated with slaked lime to convert sodium carbonate to sodium hydroxide to gain white alkali liquor, which is, again, used for pulping.

Bleached pulp is obtained by treatment with chlorine, chlorine-containing substances, or hydrogen peroxide (the cleanest way, without a danger of dioxin production). The composition of raw materials for paper production may include various combinations of cellulose, wood pulp, waste paper, adhesives (to give water-repellency), alumina (for glue fixing), kaolin or chalk (for improved printability and smoothness), dyes, etc. After mixing, the resulting composite mass is sent to a paper machine, after which the rolls of paper are transported for sale or fed to the cutting machine and the packing station.

In the process of processing wood, various wastewater products are formed. They contain acids, alcohols, ethers, aldehydes, ketones, resinous substances, metal salts, etc. The share of recycled water at wood chemical plants is up to 90% of the total runoff.

Key environmental risks associated with accidents involve damage of pulp vessels containing hazardous substances, their emissions to the environment, and the subsequent formation of chemically hazardous and explosive clouds and mixtures. The layout of storage tanks and industrial chemically hazardous substances is performed based on the measures of industrial safety: tanks are mounted on pallets; for chemical emergencies, back-up tanks and reservoirs are provided. At the P&PP, there are facilities that use and store substances in quantities exceeding the quantities specified in Annex 2 to the "Federal Law № 116-FL": oxidizing substances (acids, hydrogen peroxide) – more than 210 tons/day (limit of 200 tons), toxic substances – more than 500 tons/day (the maximum amount 200 tons).

RESULTS

Based on the chemical processes, we consider four scenarios of accidents at the P&PP with consequences for the environment: release of (I) white alkali liquor, of (II) black alkali liquor, and of (II) green alkali liquor, and (IV) the failure of the waste water treatment facilities. Since the industrial site of the Manturovo P&PP is located at the distance of 1.5 kilometers from the Unzha riverbed (Fig. 1), the direct impact, for the first three scenarios, will be to the soil and groundwater with the area of impact of less than 1 km^2 (within the industrial site). In the case of the fourth scenario, as the calculations show, the maximum area of

Fig. 1. Unzha river near Medvedevo village – about 50 km downstream from Manturovo (photo by Gunko M.)

damage for the majority of pollutants is even smaller (about 800 m^2), but they go straight into the river as the wastewater treatment plant is located on its banks.

Based on expert evaluation and statistical data on accidents at pulp and paper plants, the most likely accident at the P&PP is a local-level emergency when the boundaries of the zones of impact of damaging factors are within the limits of the industrial site; the likelihood of the emergency is 10^{-4}–10^{-6} cases per year. This puts the P&PP territory, as well as surrounding areas, in the zone of acceptable risk, in accordance with Annex "D" of the "Set of Rules № SR 11-113-2002".

Table 2 presents volumes, areas, and fees obtained considering four scenarios proposed abov e.

Thus the risk of accidents with the environmental impact (the mathematical expectation of damage per year) is:

1. White alkali liquor – 7 700 rubles per year;

2. Black alkali liquor – 3 400 rubles per year;

3. Green alkali liquor – 19 100 rubles per year;

4. Failure of wastewater treatment facilities – 8400 rubles per year.

Table 2. Emergency scenarios

	I	II	III	IV
Sphere of impact	Soil, groundwater	Soil, groundwater	Soil, groundwater	Surface water
Volume of released pollutants (m^3)	1944	3888	2916	148 531
Area of impact (m^2)	277 714	555 428	416 571	?
Damage (rub)	77.6 mln	34 mln	191 mln	84 mln

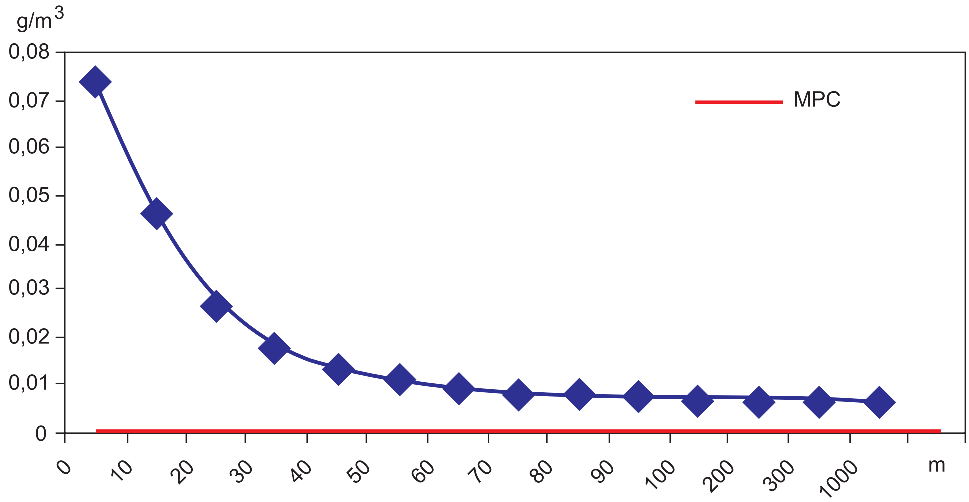

Fig. 2. Distribution function of phenols' concentrations downstream the point of discharge

Based on a series of calculations, the concentrations of pollutants in the Unzha River (the fourth scenario) exceed the MPC (Fig. 2). After 80-meter mark past the point of discharge, only phenol concentration exceeds the MPC; after the mark of 300 m, is stays around the same value of 0.070 g/m^3 without undergoing significant changes up to 1000 m.

This suggests that the increase will be observed at a significant distance from the discharge point; the accuracy of the methodology proposed above does not allow us to estimate the specific distance where phenol concentration falls below the MPC.

CONCLUSIONS

The method presented herein allows integrating fragmented information about dangers of individual enterprises in a system whose components are natural and industrial factors, various combinations of which have different effects on the formation of regional hazards in general.

This method allows taking into the account natural and socio-economic risk-factors and their influence on each other.

Clearly, any industry is harmful to the environment, but the damage must be weighed against the socio-economic benefits for the territory and its population. For a depressive peripheral area of a peripheral federal region (such as Manturovo in the Kostromskaya region), new industrial activities are very beneficial for the employment and financial stability of the population. Successful implementation of a project with the creation of new transportation, housing, and social infrastructure improves the attractiveness of the region for new projects. The question arises on the type of industry and the natural capacity of the environment sufficient for the implementation of new projects.

As we have found out in the study, the risks of accidents are of a low probability and impact a relatively small area, so the P&PP might not be as significant treat to the environment, especially if modern "green" technologies are used. One of the main problems of the status of the territory is primarily related to environmental alarmism. According to the popular public opinion, the area adjacent to the industrial enterprise will be considered "deadly" and "heavily polluted". While in the EU, for example, people live close to waste incineration plants and the industrial area in Singapore near Jurong, where one of the largest sites of oil processing world is situated, is organized into a national park. It is not that governments, scientists, and people do not realize the danger of anthropogenic impacts, but the fact that the production uses "green" technologies make these facilities acceptable. According to numerous reviews, living near the sites mentioned above does not present hazard to human health and the environment. Thus, the real danger in the light of modern safety devices (water treatment plants, filters, etc.) is greatly exaggerated.

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REFERENCES

1. Akimov, V.A., Potapov B.V., and Radaev N.N. (2001) Methods of comparative risk assessment for regions of the Russian Federation. Environment and Industry of Russia, February, pp. 25–32.

2. Akimov V.A., Lesnikh V.N., and Radaev N.N. (2004) Fundamentals of risk analysis and management in natural and technological spheres. Moscow: Delovoy Ekspress, p. 380.

3. Kasparov, G.B. (1979) Economy, organization, and planning in pulp and paper production. Forest products industry, № 4, pp. 41–58.

4. Kuzminov, I.F. (2010) Kostroma region outskirts: socio-economic consequences of forest governance transformation. Northern village: traditions and innovations. Moscow: GU-VSHE, p. 260.

5. Recommendation to action № RA 03-626-03 dated March 15, 2003 "Method for determining the size of harm that can be caused to the life or health of individuals, property of enterprises in case of accidents at hydrotechnical structures".

6. Russian Federation Government Resolution № 344 dated June 12, 2003 "About fees for air pollution from stationary and mobile sources, discharges of pollutants into surface and ground water bodies, industrial and consumer waste burial".

7. SanR&N № 4630-88 dated July 4, 1988 "Sanitary rules and norms of surface water protection from pollution".

8. Set of Rules № SR-11-113-2002 dated July 23, 2002 "Order on engineering measures of civil defense and emergency prevention when preparing a petition of intent and substantiation for investment in construction of enterprises, buildings, and facilities".

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