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Environmental Risk Related to the Exploration and Exploitation of Coalbed Methane

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Abstract: In coal seams, depending on the composition of coal macerals, rank of coal, burial history, and migration of thermogenic and/or biogenic gas. In one ton of coal 1 to 25 m³ of methane can be accumulated. Accumulation of this gas is included in unconventional deposits. Exploitation of methane from coal seams is carried out with wells from mining excavations (during mining operations), wells drilled to abandoned coal mines, and wells from the surface to unexploited coal seams. Due to the low permeability of the coal matrix, hydraulic fracturing is also commonly used. Operations related to exploration (drilling works) and exploitation of methane from coal seams were analyzed. The preliminary analysis of the environmental threats associated with the exploration and exploitation of coalbed methane has made it possible to identify types of risks that affect the environment in various ways. The environmental risks were estimated as the product of the probability weightings of adverse events occurring and weightings of consequences. Drilling operations and coalbed methane (CBM) exploitation leads to environmental risks, for which the risk category falls within the controlled and accepted range.

Keywords: coalbed methane; exploitation; exploration; environmental risk

1. Introduction

A considerable amount of methane is produced during the process of bituminous coal formation [1–4]. Biochemical and geochemical reactions and processes leading to the formation of one ton of high-ranking coals (bituminous or anthracite) produce about 200 m³ of methane [5,6]. This gas can remain in the coal or, if not sealed, escape from the seams. The CH₄ content in coal seams varies widely, between less than 1 and more than 25 m³ gas per ton, depending on the coal macerals composition, the rank of the coal, the burial history, and the migration of thermogenic and/or biogenic gas [7,8].

Depending on the location and recovery method, the following methane categories are distinguished: methane in unexploited coal beds (coalbed methane—CBM), methane in active mines (CMM—coal mine methane) and methane from abandoned mines (AMM—abandoned mine methane) [9].

Methane from unexploited coal seams is classified as an unconventional gas because the coal is both source and reservoir rock. Therefore, exploitation of CBM is different from natural gas production from conventional deposits [8]. Methane in the coal is accumulated in pores, adsorbed on the coal matrix, and sorbed into the carbon matrix [10–12]. In conventional reservoirs, most of the gas fills the pore space, while methane in coal seams is adsorbed in the coal matrix [13]. The gas in conventional reservoirs migrates to the production wells as a result of the pressure gradient. Recovery of methane

from coal seams is accomplished by reservoir pressure depletion. Gas is produced by pumping out naturally existing water. Methane is desorbed due pressure depletion, desorbing the gas that migrates through the coal matrix to the fractures (cleats) and then flows into the production well. The desorption process takes place when the reservoir pressure drops below the threshold pressure. Unexploited coal seams are saturated with water. When operating with primary methods (by lowering, steeply decreasing the pressure), the coal seams are dehydrated to start the methane desorption process. In the initial phase of extraction, mainly water is used, and gas production increases as more and more methane is desorbed. To make methane available from coal seams, it is also often necessary to perform hydraulic fracturing to increase the permeability of the coal matrix [14–16].

Methane in coal seams is extracted from coal mines (during mining), boreholes drilled into abandon coal mines, and boreholes from the surface to undeveloped coal seams [14].

Different types of wells are used to exploit methane from coal seams, which are also used in the exploitation of conventional hydrocarbon deposits. Methane is extracted by vertical wells and various types of horizontal wells. CBM uses horizontal wells drilled from a single vertical well (Z-Pinnate technology) or from multilateral horizontal wells [7,17,18].

The amount of methane produced from coal seams depends mainly on the permeability and gas saturation of the coal seams [19]. The effective porosity, permeability and saturation depend on the system of fractures in the coal. The permeability in coal seams varies from a few to several dozen mD ($1 \text{ mD} = 10^{-12} \text{ m}^2$), and its size depends on the structure and properties of the fractures network (dominant direction, continuity and width) [11,20]. Due to the low permeability of coal seams, hydraulic fracturing is used in most wells to improve the methane flow in the coal and the desorption of this gas [21].

As mentioned for the exploitation of methane from coal seams by the primary method, gas desorption from the coal matrix occurs as a result of the drop in pressure. Water and methane are extracted from the boreholes, with the initially high amount of water falling on the gas during operation [17].

Environmental risk assess the impact on humans of substances and chemical compounds produced, used, and released into the environment. The first documents on environmental risk analysis were produced in the U.S. in the 1970s [22]. In the 1980s, the Environmental Protection Agency (EPA) launched a database on the effects on human health that may result from exposure to various substances present in the environment (IRIS—Integrated Risk Information System). Subsequently, other countries developed their own procedures for assessing environmental risks, such as Australia [23], Canada [24], and the United Kingdom [25,26].

According to the definition from the EPA, environmental risk analysis is the process of determining the probability of adverse effects in the environment as a result of exposure of living organisms to one or more stressors. Developed by the EPA, the Framework for Environmental Risk Assessment distinguishes between ecological risk analysis (assessing safety in the use of chemicals, hazardous waste, emissions to the environment, impact on biodiversity, landscape changes, impact on water resources) and risk analysis for human health (the effect of stressors) [27].

An extension and update of these topics can be found in the guidelines for the Ecological Risk Assessment [28], which stresses that risk assessment and risk management are two separate activities. Risk management consists of risk assessment for human health and environmental risk assessment. They describe human populations, resources, and ecological measures, characterize the potential for adverse effects, define uncertainties, identify options for response, and provide information on threats to people and ecosystems. The report “Environmental Risk Assessment: An Australian Perspective” [29] shows that environmental risk assessment can be used as a strategic tool in business operations. “The Guidelines—Environmental Risk Assessment: An Environmental Risk Assessment and Reporting Approach” [30] can help in environmental risk assessment and the reporting of environmental conditions.

Environmental risk analysis should always be considered in the form of a case study with a drawn diagram or map of identified areas for a specific risk from source through migration paths to

the receptor [31]. The above-mentioned instructions and guidance may serve as a starting point for risk assessment and risk management. In the European Union, the risk assessment procedures are defined in the Commission Directive 93/67/EEC of July 20, 1993, laying down the principles for the assessment of risks to people and the environment of substances notified in accordance with Council Directive 67/548/EEC. The directives do not only refer to chemicals, but can also be used to analyze the risk associated with noise emissions and changes in landscape or water conditions [32].

Regulation 93/67/EEC was amended in 2006 when Regulation (Ec) No 1907/2006 of the European Parliament and of the Council of 18 December 2006, concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC was amended. REACH requires companies to identify and manage the risks associated with the substances they produce and place on the EU market. Companies must demonstrate how the substance can be used safely and are required to provide information to users on risk management measures [33].

The technologies used in the exploration, prospecting and exploitation of coal seam methane are similar to those used in conventional hydrocarbon deposits. The specificity of the coal matrix (double porosity and low permeability), the form of the occurrence of methane as a gas adsorbed on coal, means that its operation may cause environmental hazards. The article presents basic environmental aspects of the exploration and production of methane from coal seams. The hazards associated with the operation of methane from coal seams were analyzed, and their impact on the environmental elements was determined. The frequency of adverse events was also estimated. Based on the modified methodology of the initial hazard analysis, the environmental risk associated with the exploration and exploitation of CBM was assessed. The risk assessment (determination of the threats and the probability of their occurrence) was carried out on the basis of case studies presented in articles and reports.

Environmental aspects related to the exploration and exploitation of methane from coal deposits were identified for deposits in the U.S.A., Canada and Australia, i.e., countries where methane is exploited on an industrial scale. The impact of methane extraction on the quality and quantity of ground and surface water in the western U.S. [34] and in eastern Australia [35] were analyzed. The point of interest was also the problem of managing the water extracted from coal beds with methane [36]. The impacts of methane exploitation on various environment elements (water, soil, land surface, and landscape) were also analyzed [37,38], and for Alberta, a detailed environmental impact analysis was conducted [39].

There are few publications that address the risk assessment issues related to CBM technology. The risk analysis was conducted using the matter-element extension methodology in the context of the implementation of the Qinshui Basin project in southern China. The risk characteristics of exploration, mining, gathering and market application of a CBM project was presented [40]. The report prepared for the European Commission included a comparison of the risks and consequences associated with the exploitation of different types of unconventional gas (with a special focus on hydraulic fracturing operations) and measures to counteract the risk. The risks associated with CBM exploitation (site preparation, design, drilling, casing, and cementing, hydraulic fracturing, well completion and production) were assessed. For each of the stages, a range of aspects were examined: groundwater contamination, surface water contamination, water resource depletion, air, land use, biodiversity, noise, visual impact, seismicity, and traffic [41]. The issue of environmental risk assessment related to drilling operations and exploitation of coalbed methane is presented in the report prepared by the Environmental Agency. The study has presented the findings of an assessment of the environmental risks associated with the recovery of coalbed methane, coal mine methane, and abandoned mine methane. The report has provided a national overview of the environmental risks and risk management controls which regulators can use to reduce environmental impacts [42].

2. Materials and Methods

2.1. Environmental Hazards Related to CBM Exploration and Exploitation

Drilling operations carried out to make methane available from coal seams can have a negative impact on the environment in two ways. There may be adverse events associated with the operation of the drilling rig and the drilling process, and the emission of pollutants into the environment. Risks associated with the operation of drilling rigs may occur for a short period of time (up to several weeks). However, pollutants introduced into the environment can affect groundwater or soil for many years. During drilling operations, routine work can be distinguished, which usually does not pose a major threat to the environment, or an emergency, that can cause significant environmental damage.

The operation of drilling rigs can cause negative changes in all elements of the environment:

- Changes in the soil and soil structures (establishment of drilling equipment and infrastructure);
- Inhibition of plant vegetation (use of chemicals or establishment of plants);
- Pollution of the soil or surface and/or underground waters (substances migrating from the drilling site, petroleum substances, materials for the production of drilling fluids or treatment fluids);
- Excessive water exploitation (for technological and household use);
- Air pollution (emission of gasses and particulate matters from the fuel combustion in diesel engines, boiler houses, traffic);
- Noise emission (operation of equipment on a drilling rig, transport).

The drilling process and the work carried out in the borehole during the search for methane from coal seams can also pose a threat to the environment:

- Contamination of the soil and surface and/or underground water (pollutants migrating from the borehole: reservoir water, mud or drilling fluids);
- Change in the groundwater regime (creation of a hydraulic connection);
- excessive groundwater extraction for technological operations (hydraulic fracturing);
- Atmospheric air pollution (emission of gasses and particulate matters);
- Land deformations, noise emission related to certain technological operations (siphoning of wells, hydraulic fracturing).

Negative effects of drilling rigs and drilling operations on the extraction of methane from coal seams occur during routine operations in a small area for a short period of time, usually on a small scale. Most of them do not cause serious ecological damage. These impacts are less than in conventional hydrocarbon prospecting operations due to the shallower depth of the boreholes drilled. The situation is different for emergency events, which can cause large losses in the environment. A very high risk to the environment are discharges of drilling mud or reservoir fluids (eruptions) under high pressure, which can cause dangerous situations for the environment and human health (gas leaks or brine) [43,44].

Hydraulic fracturing, which is used in the extraction of coal seam methane, poses less of a threat to the environment compared to shale gas extraction. These treatments consume less water (less groundwater extraction) and therefore less flowback fluid to be disposed of [43–45].

During the process of methane exploitation from the coal seams, large amounts of waters are extracted that need to be managed. Its extraction can pose a threat to the underground water resources located in aquifers with hydrodynamic contact to methane-bearing deposits. In addition, because of the shallow depth of coal seams containing methane gas, the extraction of methane gas can potentially have a greater impact on drinking water resources than shale gas extraction. CBM production can pose a threat to surface water because large quantities of water are extracted with gas. The water should be properly managed in accordance with current regulations. The use of a large amount of exploited water requires its disposal (high intensity of road traffic), treatment and unloading may cause an increased risk of pollution of surface water (e.g., spillage, damage to the treatment plant).

The risks associated with the transport of the extracted water can also be potentially greater than in the case of shale gas. During the exploitation of methane from coal seams, there is also a potential risk of gas migration through overburden and emissions to the atmosphere due to the shallow CBM accumulation depth and lack of sealing work [43,44].

Exploitation of methane from coal seams can have negative environmental impacts, including:

- Pollution of surface and/or underground water (reservoir water, technological fluids);
- Change in groundwater conditions (establishment of the hydraulic connection);
- Air pollution (gas emissions from wells or flares);
- Noise emissions associated with certain technological treatments.

2.2. Assessment of the Environmental Risk Resulting from the Exploitation of CBM

Environmental risk includes the risks to human health and life as well as ecological risk, and it is not universally applicable [46,47]. On the other hand, the ecological risk is defined as the probability of the occurrence of events causing environmental degradation and its consequences [48]. Risk assessment is the process based on identifying, analyzing, and risk rating [49].

There are many methods of risk assessment [50] and they are used in many areas of industry and human activity [48,51–55]. All methods risk assessment can be summarized in groups:

1. Qualitative Methods for Risk Analysis—descriptive methods which do not allow the determination of a numerical value for the risk. These are methods based on expert knowledge, good practice, and experience. The risk is usually presented in the form of lists of threats (matrices, graphs) together with a relative risk assessment, e.g., brainstorming, causal mapping, checklist classification taxonomies, Delphi technique, HACCP—Hazard analysis and critical control points, HAZOP—Hazard and operability studies, interviews, Ishikawa analysis, multi-criteria analysis (MCA), risk registers, scenario analysis or a structured ‘what if’ technique (SWIFT).
2. Quantitative Methods for Risk Analysis—based on measurable quantitative data (e.g., pollutant concentration, migration time), methods of mathematical statistics and probability calculation. They make it possible to determine the numerical value of the risk to be determined. These are objective methods that require a large amount of precise input data. These methods include Bayesian analysis, cause–consequence analysis, cross impact analysis, decision tree analysis, event tree analysis (ETA), fault tree analysis (FTA), frequency/number (F/N) diagrams, game theory, Markov analysis, Monte Carlo analysis, toxicological risk assessment or value at risk (VaR).
3. Semi-qualitative Methods for Risk Analysis—combined probabilistic and descriptive methods, which include Bow Tie analysis, consequence/likelihood matrices, FME(C)A (failure modes and effects (and criticality) analysis), Pareto charts, reliability centered maintenance (RCM), risk indices and S-curves.

In the first stage, the article analyzes the environmental impact of the exploration and exploitation of coalbed methane, and in the second stage, the environmental risk associated with the exploitation of CBM was assessed using a modified hazard/probability matrix method.

The environmental risk assessment was carried out in four steps. Firstly, the scope of the analysis was determined. In the second and third stages, threats and their consequences were identified. The last part of the analysis was the assessment of the likelihood of occurrence of events with defined consequences. The risk assessment can be carried out using qualitative or quantitative methods. The choice of the method depends primarily on the availability and scope of information, knowledge of the methods of risk analysis, and the knowledge and experience of the persons performing the analysis [56].

In the case of risk assessments of the exploration and recovery of coalbed methane, a qualitative method has been proposed—a preliminary risk analysis. This is based on classification focused on a determined risk acceptance level. Briefly, which of risks can be accepted according to low probability of

their occurrence and potential danger, and on the contrary, which cannot be because of real possibilities of their incidence and related consequences. This method enables the selection of these types of risks that should be subjected to further analysis [56].

In order to assess the ecological risk, the work related to exploration (drilling) and the exploitation of coalbed methane was analyzed. The environmental risks were estimated as the product of the probability weightings of adverse events occurring and weightings of consequences [45,56]. Risks and impacts were assessed qualitatively based on expert knowledge reported in the literature. Taking into account risk analyses, [45] for adverse events that may occur during the drilling and exploitation of methane from coal seams, the probabilities of their occurrence and the following weightings were proposed [57,58]:

- Rare—adverse events causing environmental hazards that are extremely rare in industry, once every 10–20 years, value: 1;
- Unlikely—adverse events causing environmental hazards that occur rarely in industry, once every 5–10 years, value: 2;
- Moderate—adverse events causing environmental hazards in industry, not related to routine activities, once every 1–5 years, value: 3;
- Likely—adverse events causing environmental hazards in industry, occurring once or several times per year, value: 4;
- Almost certain—adverse events causing environmental hazards which occur several times per year in each CBM deposit, value: 5.

Based on the characteristics of the drilling and CBM exploitation, the following categories of environmental consequences of the occurrence of adverse events have been identified [45,57]:

- Insignificant—events that have an immediate, short-term adverse effect on the environment, which may have a significant but limited impact on the environment, and is subject to natural remediation after a few days or weeks, value: 1;
- Minor—events having an immediate or long-term (weeks or months) negative impact on the environment, which are low intensity and the environment may return to its previous state by natural means (after a long period of time) or the remediation requires physical intervention, value: 2;
- Moderate—events that have an immediate or long-term (e.g., over a period of one year) negative impact on the environment and cause chronic but not catastrophic environmental impacts, value: 3;
- Major—events which have an immediate negative impact on the environment in the short term (hours or days) and in the long term (weeks, months or years) and whose effects are eliminated within a few months; events of high-intensity which cause the extinction of flora and fauna and have significant effects on ecosystems, value: 4;
- Catastrophic—events which have an immediate and long-lasting (several years) negative impact on the environment, with serious consequences and a wide range of effects; they cause the extinction of flora and fauna, irreversible environmental damage lasting several years or damage to almost irreversible natural resources (it takes several years to return to the state before the event occurred), value: 5.

3. Results

The risk of the occurrence of adverse events during exploration (drilling) and CBM exploitation was assessed by specifying their environmental impact and determining their numerical value for individual aspects (Tables 1 and 2). An environmental aspect is a component of an organization's activities, products or services that affect or may affect the environment. In contrast, the environmental impact can be adverse or beneficial, resulting in whole or in part from the organization's activities, products or services [59].

Table 1. Environmental impact and risk resulting from coalbed methane (CBM) exploration (drilling rig locations, drilling works).

No.	Environmental Aspect	Impacts	Likelihood	Consequence	Risk
1	Groundwater pollution	Pollution: by precipitation containing substances from the drilling rig. Leaky wells can be migration paths of pollutants (drilling fluids, chemicals, or cuttings) and brines into aquifers	2	3	6
2	Groundwater pollution (failures)	Outflow of treatment fluids (corrosion protection, biocides, preventing scaling) in connection with the loss of tightness	2	5	10
3	Surface water pollution	Pollution with precipitation containing substances originating from the drilling site (sewage, oils, lubricants, fuels, or chemicals used for the preparation of drilling mud, process fluids or cement)	2	3	6
4	Surface water pollution (failures)	Damage to drilling systems or equipment for the treatment liquids	2	5	10
5	Emissions of pollutants into the atmosphere	Gases and dust emissions from boiler houses, generators, and transport	3	1	3
6	Emissions of pollutants into the atmosphere (failures)	The release of methane into the atmosphere during the eruption	1	5	5
7	Soil pollution	Precipitation containing substances originating from the drilling sites (sewage, oils, lubricants, fuels, or chemicals used for the preparation of drilling muds, process fluids or cement)	2	3	6
8	Soil pollution (failures)	Penetration of large quantities of oils, fats, fuels, or chemicals used for the preparation of muds, process fluids or cement into the soil environment	1	5	5
9	Groundwater level changes	Groundwater drawdown associated with excessive groundwater withdrawal for technological purposes	1	3	3
10	Terrain deformation	Formation of underground caverns and collapse of the surface after completion of the drilling work	1	3	3
11	Noise	Noise associated with drilling operation (generators and equipment). A high noise level occurs during work where additional aggregates are used, e.g., during cementing	5	2	10
12	Impact on the landscape	A drilling rig is very often an industrial element in an agricultural or forestry area	2	1	2

Table 2. Environmental impact and risk resulting from CBM exploitation.

No.	Environmental Aspect	Impacts	Likelihood	Consequence	Risk
1	Groundwater pollution	The exploitation of CBM at low depths causes a greater threat to groundwater pollution by methane or reservoir waters	2	3	6
2	Surface water pollution	Large quantities of water exploited with methane that must be disposed of, pose a threat to the quality of surface waters (e.g., in connection with water spills)	1	3	3
3	Surface water pollution (failures)	In case of a failure of the cleaning or transport system, surface water may be polluted	1	4	4
4	Emissions of pollutants into the atmosphere	Emissions of gases generated during the operation of devices related to the operation of CBM and the leakage of methane from the infrastructure (valves, flares)	2	2	4
5	Emissions of pollutants into the atmosphere (failures)	A leak into the atmosphere of methane in connection with a failure of operational or gas transport facilities	1	5	5
6	Groundwater level changes	Groundwater drawdown associated with the extraction of large quantities of waters	1	5	5
7	Noise	Noise emission from compressors, pumps and other equipment	3	2	6

For an evaluation purpose of an environmental risk assessment, four levels of risk were taking into consideration (Table 3).

Table 3. Categories and numerical values of risk.

Level of Risk	Score	Consequence	Color
Low	Up to 5	Acceptable	
Medium	6–12	Controlled	
High	13–19	Unacceptable	
Very high	20–25	Unacceptable	

The risk matrix for assessing risks of CBM exploration and exploitation is a simply qualitative rank of the identified risks (Figure 1). The risk matrix is the product of likelihood and consequence dependence. The highest scores are assigned to combinations of high likelihood and catastrophic consequences.

			Consequence				
			1	2	3	4	5
			insignificant	minor	moderate	major	catastrophic
Likelihood	5	almost certain	5	10	15	20	25
	4	likely	4	8	12	16	20
	3	moderate	3	6	9	12	15
	2	unlikely	2	4	6	8	10
	1	rare	1	2	3	4	5

Figure 1. Risk (consequence/likelihood) matrix.

A heat risk map is a method of presenting the resulting assessments of the likelihood of risk occurrence and the impact of the risk. It is a tool used to visually present the results of a risk assessment. In the paper, the heat maps of the risk assessment of CBM exploration and exploitation were prepared (Figures 2 and 3).

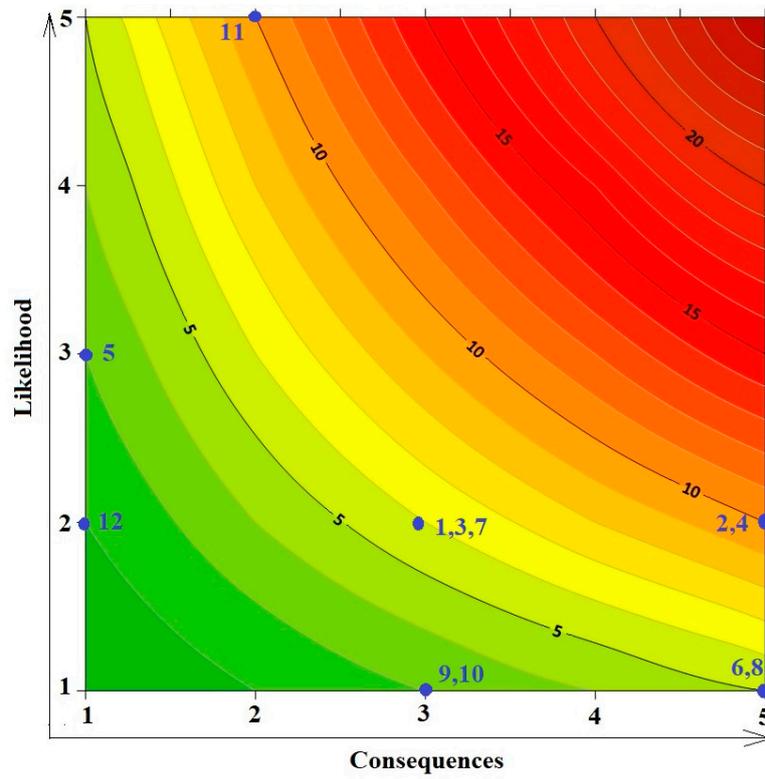


Figure 2. Risk heat map for environmental impacts of CBM exploration (drilling rig locations, drilling operations).

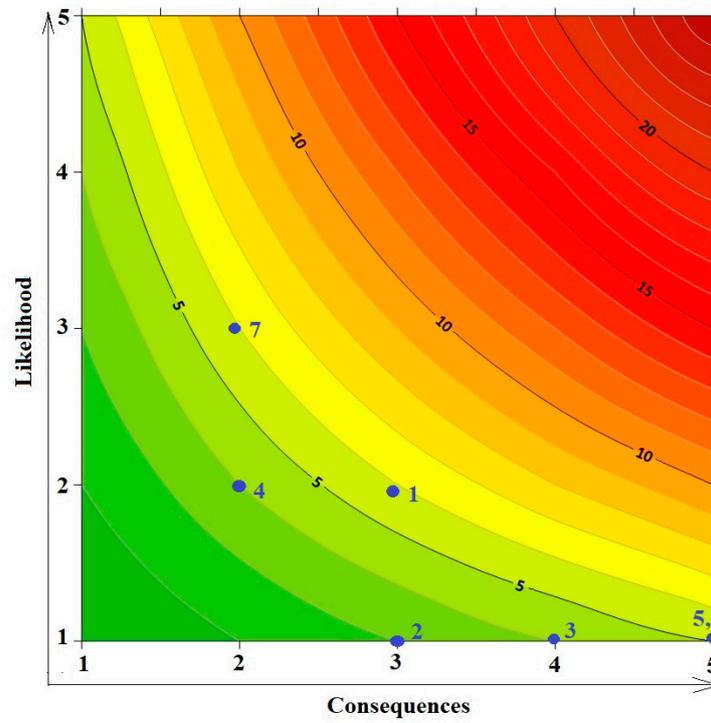


Figure 3. Risk heat map for environmental impacts of CBM exploitation.

4. Conclusions

The preliminary analysis of the environmental threats associated with the exploration and exploitation of coalbed methane has made it possible to identify types of risks that affect the environment in different ways. Risks of drilling operations and methane recovery and impacts on the environment were assessed qualitatively, based on expert knowledge informed by the literature.

The drilling works conducted until the complete extraction of the CBM give rise to environmental risks, for which the risk category acceptance falls within the controlled and tolerated range. In the area of controlled risks, these works affect the following environmental aspects: the pollution of ground and surface waters and soils in connection with routine work and failures, emissions to the atmosphere due to failures, and noise emissions. Risks related to drilling operations include emissions into the atmosphere related to routine work, changes in the location of the groundwater table, deformation of the terrain, and effects on the landscape.

The environmental risk estimated for drilling operations related to the CBM extraction indicates that there is no need to take measures to limit this risk. Well-planned and carefully carried out drilling operations using modern technology and technical measures do not generally pose a serious threat to the environment.

The exploitation of coalbed methane cause environmental risks, which contain within the controlled and tolerated range of risk acceptance. In the controlled risks area, the recovery of methane from coal seams affects the following environmental aspects: groundwater pollution associated with routine operations, emissions to the atmosphere associated with failures, changes in the groundwater level, and noise. The risks associated with the CBM exploitation are similar to those associated with drilling operations: surface water pollution related to routine operations and failures, and emissions pollutants into the atmosphere related to routine operations.

The environmental risk estimated for the exploitation of coalbed methane indicates that there is no need to take measures to limit this risk. However, it is possible to take measures that will help to maintain the unchanged state of the environment. This includes the application of all regulations concerning the performance of mining operations.

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