Management of environmental risks during and after mine closure

(MERIDA)

EUR 30412 EN

Research and Innovation

Management of environmental risks during and after mine closure (MERIDA)
European Commission
Directorate-General for Research and Innovation
Directorate D – Clean Planet
Unit D.3 — Low Emission Future Industries
Contact Hervé Martin
E-mail RTD-PUBLICATIONS@ec.europa.eu

European Commission
B-1049 Brussels

Manuscript completed in 2020.

Luxembourg: Publications Office of the European Union, 2020

PDF ISBN 978-92-76-23792-1 ISSN 1831-9424 doi:10.2777/421399 KI-NA-30-412-EN-N

EUROPEAN COMMISSION

Research Fund for Coal and Steel

Management of environmental risks during and after mine closure

(MERIDA)

Alicja Krzemień (Coordinator)
E. Krause, A. Duda, M. Wysocka, A. Frejowski, K. Kura, A. Koteras, A. Więckol-Ryk
Główny Instytut Górnictwa (GIG)
Pl. Gwarkow 1, 40-166, Katowice, Poland

J. Wagner, K. Zimmermann, M. Koch, M. Schlautmann, R. Müller-Siegert
DMT

A. Korre, S. Durucan, M. Lathouri, J.Q. Shi, W. Cao, W. Cai, H. Agrawal
IMPERIAL

Gouzy, V. Viollet, Z. Pokryszka
Ineris

J. Krawczyk, W. Dziurzyński, K. Tajduś, M. Dudek, R. Misa
IMG PAN

P. Foster, R. Crane, A. Sweeney
EXETER

P. Riesgo Fernández, F.J. Iglesias Rodríguez, A. Suárez Sánchez, P. Fernández Álvarez, A. González Quirós
UNIOVI

J. Dvoracek
VSB

J.J. Álvarez Fernández, R. Terroba Alonso, F.M. Fernández Miranda.
HUNOSA

Z. Łachan, R. Ziarno, W. Reclik, T. Szryt, M. Helios
PGG

Grant Agreement RFCR-CT-2015-00004

15/12/2015 - 15/12/2019

Final Report

2020 Directorate-General for Research and Innovation EUR 30412 EN

TABLE OF CONTENTS

1 FINAL SUMMARY 5

1.1 WORK PACKAGE 0: PROJECT COORDINATION...................................... 5

1.2 WORK PACKAGE 1: GIS TOOL DEVELOPMENT, COLLECTION AND ORGANISATION OF DATA 5

1.3 WORK PACKAGE 2: DEVELOPMENT OF ENVIRONMENTAL IMPACT ASSESSMENT MODELS FOR COAL MINE CLOSURE AND POST-CLOSURE PERIODS 6

1.4 WORK PACKAGE 3: RISK EVALUATION 8

1.5 WORK PACKAGE 4: RISK MANAGEMENT AND REMEDIATION MEASURES .. 9

1.6 WORK PACKAGE 5: DISSEMINATION 10

1.7 CONCLUSIONS 11

1.8 POSSIBLE APPLICATIONS AND PATENTS... 12

2 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS...................... 13

2.1 OBJECTIVES OF THE PROJECT 13

2.2 COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED... 13

2.3 DESCRIPTION OF ACTIVITIES AND DISCUSSION................................ 13

2.3.1 Work Package 1: Gis Tool Development, Collection & Organisation Of Data 13

2.3.2 Work Package 2: Development of Environmental Impact Assessment Models for Coal Mine Closure and Post-Closure Periods 25

2.3.3 5.3.3 Work Package3: Risk Evaluation 56

2.3.4 Work Package 4: Risk Management And Remediation Measures................ 86

2.3.5 Work Package 5: Dissemination 93

2.4 CONCLUSIONS 93

2.5 EXPLOITATION AND IMPACT OF THE RESULTS 96

LIST OF FIGURES 99

LIST OF TABLES... 103

3 GLOSSARY.. 105

REFERENCES 107

1 FINAL SUMMARY

1.1 WORK PACKAGE 0: PROJECT COORDINATION

WP Leader: ***GIG*** *Partners****: GIG, DMT***

The main objective of this work package was to perform the general management of the different project elements, in order to assure the smooth progress of the project and the efficient use of resources, as well as supplying the Commission with the First, Second, Mid-Term, Third and this Draft Final Report.

This task also comprised the activities carried out in order to set-up and maintain the project website, which was used for collaborative information sharing in a private area.

This WP also included the coordination of the different meetings of the partners that took place during the development of the project.

1.2 WORK PACKAGE 1: GIS TOOL DEVELOPMENT, COLLECTION AND ORGANISATION OF DATA

WP Leader: ***DMT***

*Partners****: GIG, IMPERIAL, INERIS, IMG PAN, EXETER, UNIOVI, VSB, HUNOSA, PGG***

OBJECTIVES OF WP1

The general objective of this work package was to establish the framework for the collection and compilation of relevant data related to environmental impacts during the coal mine closure and post-closure stages.

In addition, it established the risk criteria used as benchmark for environmental risk assessment.

Different operational, geological and environmental conditions relevant to European coal mines were considered and a dedicated spatial data management and visualisation tool were designed.

The main objectives were:

- G1.1. To prepare a full description of the Polish and Spanish coal mines being assessed and collect relevant data as well as historical information on environmental incidents and their impacts.
- G1.2. To conduct a survey of experiences and related environmental impacts and risks following coal mine closure across Europe, aimed at generalising the management system developed under G1.4.
- G1.3. To define the risk assessment criteria for each environmental impact category considered.
- G1.4. To design and make available to the partner coal mines a dedicated Geographic Information System (GIS) database to manage the necessary mine, geological and environmental data, which will also be used to manage information input to Work Packages 2-5.

Task 1.1 Collect background information and new environmental monitoring data from the selected PGG and Hulleras del Norte mines

It was divided into four subtasks:

Task 1.1.1 Collection of background and available environmental data from the selected mines

The work within this task was to provide background information and new environmental monitoring data from the selected mines. All the information needed to develop the project related with Rydułtowy-Anna Mining Complex was collected and uploaded in the intranet. The same kind of information was collected and uploaded in the intranet for Mosquitera and Pumarabule Mines, although it was possible to add information about the flooding process, historical damages and incidents and the specific mine’s urban plans.

Task 1.1.2 Laboratory experiments to evaluate long term gas flow after mine flooding

Experiments were carried out to establish degassing properties of coal samples (i.e. CH_4 emissions) under water pressures. The objective was to quantify the influence of water pressure that will evolve during and after mine flooding, on CH_4 emissions. Results shows that with increasing pressure on the water layer, the pressure increase in the air cushion decreases, which means that the methane emission is inhibited.

Task 1.1.3 Soil gas flux measurement (baseline) at the selected PGG and Hulleras del Norte mines

Ineris undertook a first measurement campaign in summer conditions in the area of old closed Anna mine in September 2016. UNIOVI undertook a measurement campaign during the month of November 2016, with a similar device than the one used by Ineris. Parallel to CO_2 and CH_4 flux measurements also measurements of radon emission from soils and grounds in mining and post-mining areas were performed in Poland and Spain. From this point, the drivers of mine gas migration to the surface were described and explained. Second, threshold values were presented with usual values as well and anomaly thresholds according to previous Ineris studies. Third, the field measurements performed within the project were reported and analysed. Four, coupled with of all the local expertise, a reference guide on soil gas monitoring in coal mining regions was delivered.

Task 1.1.4 Discharged water quality measurements at the selected PGG and Hulleras del Norte mines

Water quality data for the selected mines (Mosquitera and Pumarabule Mines and Rydułtowy-Anna Mining Complex) was provided to evaluate the hydrogeology and assess the surface water environmental impacts of mine closure.

Task 1.2 Collect historical data related with environmental incidents and risks following closure in European coal mines

Reviews were undertaken on different types of post-mining hazards (defined as "anything with the potential to cause harm") associated with both closed and abandoned coal mines that have caused past incidents. These are presented on a country by country basis. Based on these reviews, a report on historical data related with environmental incidents and risks following closure in European coal mines was delivered, with significant hazards grouped into one of three generic categories: sinkholes and shaft incidents, gas emissions, and mine water discharges.

Task 1.3 Definition of risk criteria

A comprehensive report and analysis of coal mine closure risk criteria for ground movement, surface and groundwater pollution, sediment and soil pollution and air pollution (including GHG and radon) was developed.

Then, risk criteria were defined for every environmental risk factor considered in the project (ground movement, air quality, and ground and surface water quality) in order to set the benchmark of acceptable thresholds against which risk evaluation will be carried out.

Task 1.4 Setup and development of the GIS data management and visualization tool

The spatial data management and visualization tool was set up in a virtualized UNIX environment running at DMTs datacenter. The WebGIS-Application was developed as a client framework for spatial data infrastructures. The tool can be freely accessed at: https://safeguard.dmt.de/merida/?lang=en.

1.3 WORK PACKAGE 2: DEVELOPMENT OF ENVIRONMENTAL IMPACT ASSESSMENT MODELS FOR COAL MINE CLOSURE AND POST-CLOSURE PERIODS

WP Leader: ***IMPERIAL***

*Partners**: GIG, DMT, Ineris, IMG PAN, UNIOVI, HUNOSA, PGG***

OBJECTIVES OF WP2

The general objective of this work package was to develop site specific issue based models to evaluate quantitatively the environmental impacts during coal mine closure and post-closure periods in different European coal mining regions and, using these models, demonstrate the functionality of the GIS based environmental management system developed in WP1.

- G2.1. To use geomechanical and surface deformation modelling methods to evaluate the ground movement potential for a selected PGG and HUNOSA mine; validate and assess modelling results; consider modelling uncertainty given historical and newly collected monitoring data; identify the structures/receptors at risk and evaluate the environmental risk exposure.

- G2.2. To use hydrological modelling software to simulate groundwater flow and solute transport at the selected PGG and HUNOSA mines; validate and assess modelling results; consider modelling uncertainty given historical and newly collected monitoring data; identify the structures/receptors at risk and evaluate the environmental risk exposure.
- G2.3. To use aqueous water geochemistry software tools to model the surface water quality and pollutant bioavailability around selected PGG and HUNOSA mines; validate and assess modelling results; consider modelling uncertainty given historical and newly collected monitoring data; identify the structures/receptors at risk and evaluate the environmental risk exposure.
- G2.4. To model and estimate gaseous emissions to the surface from coal mines during closure and post-closure periods at the selected PGG and HUNOSA mines; validate and assess modelling results; consider modelling uncertainty given historical and newly collected monitoring data; identify the structures/receptors at risk and evaluate the environmental risk exposure.
- G2.5. To integrate the environmental impact assessment results in the web-based GIS visualisation tool.

Task 2.1 Development and validation of detailed models to assess the effects of subsidence and demonstrate their implementation at the selected PGG and HUNOSA mines

The models addressed geomechanical and surface deformation, which would allow to proper describing the behaviour of rock mass in a region of flooded coal mines.

Work was focused on selecting the suitable model describing the behaviour of rock mass fracture. Mediums density change method was propose to achieve proper calculations. The results of the models allowed obtaining the distribution of deformation indicators on the ground surface, such as displacements or stresses. In addition, distribution of these indicators in the rock mass were achieved.

Task 2.2 Development and validation of detailed models to assess the groundwater pollution impacts and demonstrate their implementation at the selected PGG and HUNOSA mines

The work included the analysis of information of the mines under study, the building of the conceptual groundwater models, the implementation in the numerical software and the results and validation of numerical flow and transport models. In the case of Mosquitera and Pumarabule Mines, it has been developed a groundwater flow and solute transport in flooded underground coal mines by means of COMSOL Multiphysics. In the case of Rydułtowy-Anna Mining Complex, a groundwater chemical flow model to estimate the environmental impact associated with water rebound was developed by means of FEFLOW.

Task 2.3 Development and validation of detailed models to assess the surface liquid emissions and surface water pollution impacts and demonstrate their implementation at the selected PGG and HUNOSA mines

Based on the discharged water quality measurements at the selected mines, the aqueous water geochemistry software WHAM7 and bioavailability M-BAT tool was used to model the water quality and pollutant bioavailability. The discharged water quality (or surface water quality) was modeled with the Windermere Humic Aqueous Model. The output of the models provided the component complex concentrations in the aqueous phase, the free ion activity and the fraction of each component for each of the colloidal phases.

Task 2.4 Development and validation of detailed models to assess the greenhouse gas emissions from closed mines on surface and their implementation at the selected PGG and HUNOSA mines

In the first place, the estimation of future emission rates, reduction due to abandonment and influence of flooding was developed. In second place, by using the Ventgraph software, validated models of methane flow paths and methane concentrations in individual areas of the mine were developed. In third place, the mathematical model of firedamp reservoir developed by Ineris was applied. Results determined the places of possible gas outflow to the surface.

Another result was the implementation of a Ventgraph Radon module modelling radon exhalation, its radioactive decay and the losses during transport in the ventilation system of a mine.

Task 2.5 Integration of environmental impact estimates in the ArcGIS database

The modelling results were integrated in the database and the web-based visualisation environment, allowing the joint interpretation in the Web-GIS integrated modelling system: ground movements, groundwater transport, gas risk areas, hydraulic heads, water chemical analysis, surface deformation damages, hydraulic velocities, flood probabilities, etc.

An analytic tool was developed in order to allow the user to develop measures, cross sections and heatmaps, in order to analyse interactions among any variables. In addition, another tool was developed to allow used friendly comparison of different water chemical parameters over time.

1.4 WORK PACKAGE 3: RISK EVALUATION

WP Leader: ***GIG***

*Partners****: DMT, IMPERIAL, Ineris, IMG PAN, UNIOVI, HUNOSA, PGG***

OBJECTIVES OF WP3

The general objective of this work package was to undertake a risk evaluation based on the results of the data collection and environmental impact predictions carried out (WP1 and WP2), including the assessment of the assumptions made, the limitations of the tools used, and possible site evolution scenarios for the coal mines during the post-closure period. Possible risk treatment strategies were identified and considered in terms of the integrated risk profile of coal mine sites.

Specific objectives of the WP3:

- G3.1. To perform risk evaluation and compare the estimated levels of risk with the risk criteria previously defined for each individual topic of concern (ground movement, groundwater, surface water and gaseous emissions).
- G3.2. To decide which risks need treatment and establish the priorities for treatment considering the relationships between rock mass movements, gaseous, ground and surface water impacts.
- G3.3. To determine the mitigation alternatives that can be used for each risk that needs treatment in order to reduce them to an acceptable level.

Task 3.1 Report on the risk evaluation; identification and prioritization of areas exposed to subsidence risk and proposed treatment at the selected PGG and HUNOSA mines

The main objective of this task was to assess the risk of continuous and discontinuous deformations because of the liquidation works carried out in the mines. As mentioned in previous studies, the liquidation of underground mining excavations through flooding involves certain geomechanical problems associated with changes in the properties of rock mass and the pressure inside. The arising movements occurring in the rock mass due to these changes can lead to damage of buildings located on the ground surface. The results of this assessment were used to identify ground movement risk treatment alternatives relevant for different sites and environmental conditions.

Task 3.2 Report on the risk evaluation; identification and prioritization of areas exposed to groundwater risk and proposed pollution treatment at the selected PGG and HUNOSA mines

The events considered based on the established context were floods, pollution of underground aquifers and flooding of other mines, which allowed identifying the following risks: extremely heavy rain, pumping failure, groundwater rebound after mine closure, interaction with other aquifers and interaction with other mines. Then these risks were evaluated, identifying and prioritising the exposed areas. Finally, treatments were proposed for each different risk.

Task 3.3 Surface water pollution risk assessment at the selected PGG and HUNOSA mines

For the aquatic toxicity assessment, hazards and sources of harm were identified. Environmental quality standards together with the environmental exposure concentration were used to screen for contaminants present and detect if any of them may pose an environmental risk. The chemical and aquatic toxicity risk analysis results were used to produce a risk index for each particular contaminant, allowing to compare the results with established risk criteria and determine the consequence/probability of any adverse effect and when additional action is required.

Finally, as the risks were associated with iron, sulphates and chlorides, treatment systems were proposed for each of them.

Task 3.4 Gaseous emissions risk assessment at the selected PGG and HUNOSA mines

The hazard associated with the emission of gases to the surface during and after mine closure were evaluated, depending mainly on the intensity/amount of the gases in mine workings and the occurrence of structures and places which enable migration of the gases to the surface. The areas where gas emission to the surface can occur were identified, maps of risk areas for gas migration were produced and different treatments were proposed according to the risk evaluations. In addition, the areas where radon emission to the surface and its penetration into buildings can occur were identified and potential treatments were proposed.

Task 3.5 Regional integration of different risk components

In order to consider how proposed risk mitigation strategies which address a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk). Noted that all of the risk components were interrelated, as either a cause or consequence of another component with "flooding due to rising groundwater" a contributing cause for all. As a result, a separate BTA for the event of rising groundwater was drawn up, showing the relationships between the impacts, and allowed the identified of mitigation alternatives that could reduce the risk further.

1.5 WORK PACKAGE 4: RISK MANAGEMENT AND REMEDIATION MEASURES

WP Leader: ***UNIOVI***

*Partners**: GIG, DMT, IMPERIAL, Ineris, IMG PAN, HUNOSA, PGG, VSB***

OBJECTIVES OF WP4

The general objective of this work package was to evaluate the performance of alternative risk mitigation strategies in terms of performance (reducing the risk to acceptable levels) and cost. The final closure assessment plan was elaborated by means of selecting the most feasible treatment alternatives for the different environmental impacts together with the transitional monitoring that could guarantee a hazard level in compliance with land re-use and use of natural resources (e.g. water).

Specific objectives of WP4:

- G4.1. To forecast the performance of different pollution treatment methods in order to mitigate risks, use the models developed in WP2 and estimate the emissions and corresponding reduced risk levels.
- G4.2. To carry out a cost analysis of the different pollution treatment alternatives in order to support the selection of the most feasible for each case.
- G4.3. To estimate treatment failure probabilities and their uncertainty bounds, based on the project's timeline in order to redesign and improve the treatment strategy.
- G4.4. To define the cost efficient transitional monitoring and validation programmes that should be implemented to verify impact assessment and compliance.
- G4.5. To establish a methodology to estimate financial provisions needed for monitoring and mitigation during coal mine closure and post-closure periods.
- G4.6. To elaborate the final closure assessment report for the selected PGG and Hullera del Norte mines.

Task 4.1 Forecasting the performance of the selected treatment options in terms of impacts and risks

The environmental performance of the pollution treatment strategies was analysed for the different risks. For groundwater risk management, permeable reactive barriers, piezometric controls with powered water level alarm sensors, weather stations and hydrochemical laboratory control analysis and head monitoring were considered, depending of the specific mine addressed. For surface water risk management, settling ponds and aerobic wetlands for risks associated with iron, cost effective sulphates removal process for risks associated with sulphates and vacuum evaporation for risks associated with chlorides were considered. For ground movement risk management, the monitoring of structures and specific measures for newly designed buildings were considered. Finally, for gas risk management, flares or gas vents and gas monitoring in buildings were considered and, in the case of radon, ventilation, sealing of cracks and fissures, and the used of specialized building foils.

Task 4.2 Cost analysis of the pollution treatment options

This task was focused on the cost analysis of the selected pollution treatment options for each of the studied mines. A detailed description of the different investment and costs needed for the different pollution treatments were presented. Taking all of them into account, Net Present Values (in fact cost present values, as there are no positive cash flows) were calculated, in order to determine the financial provisions required for closure and post-closure stages. Then, sensitive analysis of the calculations were developed, followed by uncertainty analysis. Taking also into consideration that some hazards were no feasible to be treated, a financial provision that, although cannot be used to fight against these hazards will allow the government to develop specific policies addressing the most impacted areas, was estimated. Finally, the financial provision that each company should provide in order to face all the costs to fight the different environmental risk was also estimated.

Task 4.3 Estimating treatment failure probabilities and their uncertainty bounds, based on the project's timeline

Bowtie analysis was selected according to IEC/ISO 31010: 2009. Through their analysis it was noted that all of the risk components were interrelated, either as a cause or consequence of another component with "flooding due to rising groundwater" a contributing cause for all. As a result, a separate BTA for the event of rising groundwater was drawn up. Finally, the BTA's have also shown the relationships between the impacts, and allowed the identified of mitigation alternatives that could reduce the risk further. It was proved unviable to be developed via Probabilistic Risk Assessment (PRA), due to the inexistence of available data regarding the risks addressed within the project. Thus, and according to IEC/ISO 31010: 2009, an adequate methodology to address how a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk), was the Bowtie analysis, so this was the methodology used.

1.6 WORK PACKAGE 5: DISSEMINATION

WP Leader: ***EXETER***

*Partners**: GIG, DMT, IMPERIAL, Ineris, IMG PAN, UNIOVI, VSB, HUNOSA, PGG***

OBJECTIVES OF WP5

This work package refers to the actions that was undertaken to disseminate the results of the project to coal mines across Europe and to establish links and relations with the scientific community and other research teams working in the area of management of environmental risks during and after coal mines closure.

Specific objectives of WP5:

- G5.1. To produce a best practice guideline for the management of environmental impacts, prediction and risk during coal mine closure and post-closure.
- G5.2. To ensure that the impact modelling and risk management methodologies are transferred to coal mines across Europe.
- G5.3. To ensure that the project has an impact on competitiveness of the coal mining sector.
- G5.4. To support the dissemination of the project results to the scientific community and the general public.

Task 5.1 Produce a best practice guideline for the prediction environmental impacts and the management of risk during coal mine closure and post-closure

An "Environmental impact prediction and risk management methodology for coal mine closure and post-closure" covering terrain deformation, ground and surface water and gaseous emissions was developed, documented as a recommendation for good practices. The aim being to provide a tool for coal mining companies and regulators that can be used to deal with the major environmental risks during underground coal mine closure and post-closure periods in a structured and systematic manner, both qualitatively and quantitatively.

Task 5.2 Workshop on Environmental Impact Prediction and Risk Management for Coal Mine Closures

A Workshop on environmental impact prediction and risk management for coal closure and post closure was celebrated, making it coincident with an important mining congress organized by GIG on the 6th-7th November 2019, in the SPA Hotel Jawor, Turystyczna Street 204, 43-384 Jaworze. The methodology and results generated during the project were presented in English and in Polish during the 6th of November, within a special session for the MERIDA project. Thirteen presentations about the project were delivered, covering all the main aspects.

Task 5.3 Scientific publications and conferences

Five publications about the project were delivered in very high impact journals, as well as eleven publications or congress presentations.

1.7 CONCLUSIONS

The first step of MERIDA project was to establish the framework for the compilation of relevant data related to environmental impacts during the coal mine closure and post-closure stages. A full description of the Polish and Spanish coal mines being assessed was prepared and relevant data as well as historical information on environmental incidents and their impacts was collected.

In second place, the risk criteria that was used as benchmark for environmental risk assessment was established for each impact category considered, in order to set the acceptable thresholds against which risk evaluation will be carried out.

From this starting point, site specific issue based models were developed and validated, in order to evaluate quantitatively the environmental impacts during coal mine closure and post-closure periods:

1. Development and validation of a geomechanical and surface deformation model, which would allow to proper describing the behaviour of rock mass in a region of flooded coal mines. Mediums density change method was selected as the most suitable. The results of the models allowed obtaining the distribution of deformation indicators on the ground surface, such as displacements or stresses. In addition, distribution of these indicators in the rock mass were achieved.
2. Development and validation of detailed models to assess groundwater pollution impacts. Two programmes were used: In the case of Mosquitera and Pumarabule Mines, a groundwater flow and solute transport model in flooded underground coal mines was developed by means of COMSOL Multiphysics. In the case of Rydułtowy-Anna Mining Complex, a groundwater chemical flow model to estimate the environmental impact associated with water rebound was developed by means of FEFLOW.
3. Development and validation of a surface water quality and pollutant bioavailability model by means of the aqueous water geochemistry software WHAM7 and bioavailability M-BAT tool. The surface water quality was also modeled with the Windermere Humic Aqueous Model. The output of the models provided the component complex concentrations in the aqueous phase, the free ion activity and the fraction of each component for each of the colloidal phases.
4. Development and validation of a modelto estimate future gas emission rates, reduction due to abandonment and influence of flooding, as well as estimating methane flow paths and methane concentrations in individual areas by means of the Ventgraph software. Also, a mathematical model of firedamp reservoir developed by Ineris was applied. Results determined the places of possible gas outflow to the surface. Another result was the implementation of a Ventgraph Radon module modelling radon exhalation, its radioactive decay and the losses during transport in the ventilation system of a mine.

The modelling results were integrated in a database and a web-based visualisation environment, allowing the joint interpretation in the Web-GIS integrated modelling system of ground movements, groundwater transport, gas risk areas, hydraulic heads, water chemical analysis, ground movement damages, hydraulic velocities, flood probabilities, etc.

An analytic tool was developed in order to allow the user to develop measures, cross sections and heatmaps, in order to analyse interactions among any variables. In addition, another tool was developed to allow used friendly comparison of different water chemical parameters over time.

After the models were developed, evaluated and integrated in the Web-GIS, they were used to perform a risk evaluation in order to compare the estimated levels of risk with the risk criteria previously defined, and to decide which risks need treatment. Possible risk treatment strategies were identified.

The following step was to evaluate the performance of the alternative risk mitigation strategies in terms of performance (reducing the risk to acceptable levels) and cost. A detailed description of the different investment and costs needed for the different pollution treatments were presented.

Taking all of them into account, Net Present Values (in fact cost present values, as there are no positive cash flows) were calculated, in order to determine the financial provisions required for closure and post-closure stages. Then, sensitive analysis of the calculations were developed, followed by uncertainty analysis.

Taking also into consideration that some hazards were no feasible to be treated, a financial provision that, although cannot be used to fight against these hazards will allow the government to develop specific policies addressing the most impacted areas, was estimated.

Finally, the financial provision that each company should provide in order to face all the costs to fight the different environmental risk was also estimated.

1.8 POSSIBLE APPLICATIONS AND PATENTS

Although no patents were foreseen, the methodology developed during the MERIDA project and delivered in the best practice guidelines titled "Environmental impact prediction and risk management methodology for coal mine closure and post-closure" will be a documented recommendation for good practices addressing coal mining companies in the closure process. The aim being to provide a tool for coal mining companies and regulators that can be used to deal with the major environmental risks during underground coal mine closure and post-closure periods in a structured and systematic manner, both qualitatively and quantitatively.

2 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1 OBJECTIVES OF THE PROJECT

The MAIN aim of MERIDA project was to minimise the environmental impacts and risks during the mine closure and post-closure periods in accordance with the general principle that the mine must take responsibility and minimise all risks that can be foreseen.

Other objectives of MERIDA were:

- To provide specific guidance on the issues that need to be considered when assessing the environmental impacts from coal mines at closure and post-closure stages.
- To identify the physical and chemical processes that affect environmental risks during mine closure and post-closure period and establish monitoring and modelling methods that should be implemented in order to make reliable environmental impact predictions.
- To establishing an integrated risk assessment methodology.
- To provide a practical methodology that can be used for the evaluation of risk remediation measures in terms of their performance in risk reduction, practical implementation and cost.

2.2 COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACCOMPLISHED

All planned work has been performed and completed with the followings exceptions:

1. Task 4.3 Estimating treatment failure probabilities and their uncertainty bounds based on the project's timeline, was proved unviable to be developed via Probabilistic Risk Assessment (PRA), due to the inexistence of available data regarding the risks addressed within the project. According to IEC/ISO 31010: 2009, an adequate methodology to address how a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk), was the Bowtie analysis, so this was the methodology used in Task 4.3 and presented in Deliverable 3.5.
2. It was not possible to develop a ground movement analysis of Mosquitera and Pumarabule Mines in Spain, due to the absence of monitoring measures. The analysis was made in the Candín mine (HUNOSA) instead of Mosquitera and Pumarabule Mines, as a geodetic control was made in Candín during the flooding in order to validate the model developed during MERIDA.
3. It was not possible to develop a gas analysis of Mosquitera and Pumarabule Mines (HUNOSA), as they were completely flooded when the project started. The analysis was made in Santiago and San Antonio mines (HUNOSA) instead of Mosquitera and Pumarabule Mines in order to validate the model developed.

2.3 DESCRIPTION OF ACTIVITIES AND DISCUSSION

2.3.1 WORK PACKAGE 1: GIS TOOL DEVELOPMENT, COLLECTION & ORGANISATION OF DATA

Task 1.1 Collect background information and new environmental monitoring data from the selected PGG and Hulleras del Norte mines (**led by **GIG)

T1.1.1 Collection of background and available environmental data from the selected mines *(**GIG**, UNIOVI, PGG, HUNOSA)*

Task 1.1.1 aimed at providing background information and new environmental monitoring data from Kompania Węglowa's (at present PGG) mine, i.e. Rydułtowy-Anna Mining Complex, and from Hulleras del Norte, S.A. (HUNOSA) mines, i.e. Mosquitera and Pumarabule Mines.

RYDUŁTOWY-ANNA MINING COMPLEX (POLAND)

Rydułtowy-Anna Mining Complex is partly abandoned. Between 2004 and 2016 Rydułtowy coal mine (as Operation I) and Anna coal mine (as Operation II) were a joint operations mine called Rydułtowy-Anna Mining Complex. Since 2016 Rydułtowy coal mine has been a part of Polska Grupa Górnicza (PGG), whereas Anna coal mine was closing its activity in Społka Restrukturyzacji Kopalń (SRK).

First part of the deliverable provides geological information together with photos, a boundary map and a topographic map of the mining areas of Rydułtowy-Anna Mining Complex.

Second, to illustrate geological situation in the mines accurately, geological cross sections and profiles of selected deposits were also presented in the Deliverable. This part also includes information on tectonic structures of the Upper Silesian Coal Basin, tectonics and main faults.

The next part is devoted to the description of the hydrogeological and hydrological conditions, including the drainage system and hydraulic connections between Rydułtowy coal mine and Anna coal mine.

This information is provided together with the schematics of the drainage system and hydraulic connections between the mines as well as system of water transport. Main areas of hydrogeological hazards are described for Rydułtowy mine as water hazards do not exist in the undermo reservoir located in Anna coal mine.

In fourth place, problems related to natural hazards are described. The consequence of difficult geological and mining conditions produces mining hazards like: seismicity and bursts, endogenous fires; ignition and explosions of methane and dust; water, climatic, radiation and caving-in hazards and others.

The fifth part contains the GIS information system of the general urban plan of the studied area, together with specific land use plans i.e. maps containing information on the structure of land use, conditions of land development, main elements of the spatial structure with the indication of location of the active mine shafts.

The sixth part addresses ventilation and gas emission issues.

The seventh part contains all relevant data on underground water, surface reservoirs and sewage in the mines.

The last part provides information on current and historical exploitation. This part also includes short information regarding future of the mine.

MOSQUITERA AND PUMARABULE MINES (SPAIN)

The selected "Hulleras del Norte S.A." (HUNOSA) mines are the Mosquitera and Pumarabule Mines. The set of Mosquitera and Pumarabule Mines has a surface area of around 30 km^2 and a deep between 200 and 600 m. The area comprises the following pits: Pumarabule 1, Pumarabule 2, Mosquitera 1, Mosquitera 2, Rosellón and Saús, besides several old mountain mines in the area. The study focus on Mosquitera 1 and 2, and Pumarabule 1 and 2 pits.

First, geographic situation of the mines is described, and topographic maps. It follows a description of the mines, with their galleries, information about the exploited seams and existent connections between the two mines.

Also, and in order to allow a proper study of gas emissions to surface and to analyze the influence of the galleries that are not yet submerged or that were submerged recently, a map with a surface projection of the superficial galleries was prepared (first floor in both cases: not flooded in the case of Pumarabule mine and flooded in the case of Mosquitera mine). Finally, a map with the location of other mines in the area (Rosellón and Saús) was presented, together with the study mines.

In second place, geological map of the area is provided, together with a geological profile and the stratigraphic columns of the two mines, as well as geological and geotechnical information of the mines.

In third place, hydrogeology and hydrology of the study area is addressed. Hydrogeological maps at scales 1:200 000 and 1:1000 000 are provided, plus the hydrogeological unit of the study area. Also, the historical pumping data of both mines was collected, as well as pumping data after mine flooding.

In fourth place, historical damages and incidents of both mines were collected and mapped.

In fifth place, a GIS information system of the general urban plan of the study area was included, as provided by the local authorities, together with the specific mines' urban plans.
In sixth place, the flooding process of the mines was described. Data is provided about the monitoring of the flooding process, giving the dates, m.o.s.l. (meters over sea level), and distance of water from the pit head.

In seventh place, ventilation items were addressed. As all Mosquitera mine floors were flooded, and only first floor in Pumarabule is not flooded, it was necessary to select a different set of mines in order to allow a proper study of ventilation aspects within working and closing mines as required in Work Package 2. That is why Santiago and San Antonio mines, from the Aller Area of HUNOSA, that are inter-connected, were selected. San Antonio is closed while Santiago is still under operation. Ventilation schemes of both mines are provided, as well as the ventilation scheme of the Aller Area.

Also and in order to facilitate the calculations, section of the galleries of the Aller Area were collected, as well as the ventilation measures from 2013 to 2016.

In eighth place, Mosquitera mine gas emissions from the pit head were measured during the first year of the project, as its pit head is accessible for measuring gas emissions. Pumarabule pit head is not accessible for measuring gas emissions.

In the ninth and last place, water quality aspects were addressed. First, it has to be pointed out that while Mosquitera and Pumarabule Mines were within the flooding process, there was no water quality analysis. On the other hand, the Asturias Mining Authority didn't set any water quality parameters for the pumping water. HUNOSA was only requested to measure every three months the following parameters: electrical conductivity, pH, Fe_{tot}, and SO_4, according to the flooding study presented by HUNOSA for the closing process.

T1.1.2 Laboratory experiments to evaluate long-term gas flow after mine flooding (Ineris)
Laboratory tests were carried out to establish degassing properties of coal samples (i.e. CH4 emissions) under water pressures. The objective was to quantify the influence of water pressure that would evolve during and after mine flooding, on CH4 emissions.

Conducting tests of desorption and emission of methane from coal samples submerged in water, affected by hydrostatic pressure of water column, is important in the context of methane emission in distressed undermined and overmined seams in flooded mines.

Methane emission into longwall goafs and areas which were sealed off after mining operations influence methane hazard in goafs and closed underground mine workings.

The volume of emission of methane into goafs is influenced by the volume of distressed coal seam and its original methane content within the distressed area. Releasing methane from unmined seams, distressed as a result of mining operations, usually lasts for 15 to 20 years.

Success of the tests means determination of influence of changes in hydrostatic pressure of water column on intensity of methane desorption from distressed coal seams in the vicinity of examined seam. The conducted tests provided data necessary to develop a model of releasing methane into goafs of a mine during closure.

For each coal samples (four from HUNOSA and four from PGG), five batch experiments were performed in parallel and under different water pressures, plus one blank in dry conditions.

Results for experiments on dry samples help understanding methane-degassing process from dry coal before mine flooding. These results are useful as they were used as reference values when interpreting experiments performed on wet samples.

As an example, Figure 2-1 shows methane release from dry coal during time at two experimental pressures (P_{exp} = 1 bar and 15 bars). The light blue curve helps defining the maximum quantity of methane that can be released from coal whatever the experimental conditions (e.g. 25 mmol). On the purple curve, the plateau is lower (~16 mmol) because the higher pressure of free gas phase in the batch limits methane desorption.

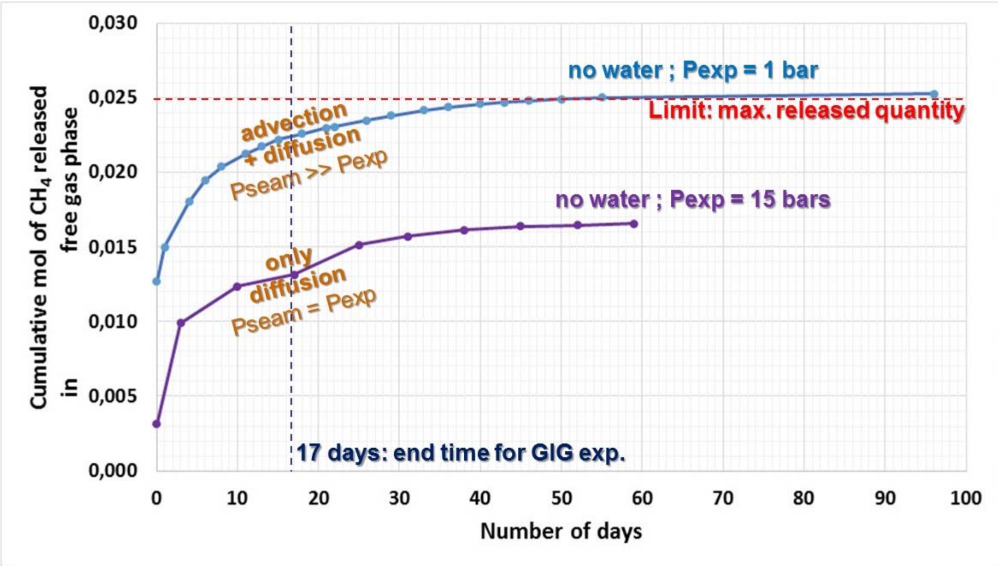


Figure 2-1. Methane release from dry coal under different free gas phase pressures

Increasing hydrostatic pressure seems to slow the desorption kinetics. This effect is clearly shown by comparing experiments at P_{exp} = 1 bar and P_{exp} = 30 bars.

However, it has to be further characterized at 10 bars and 15 bars, because results were not reproduced or are not reproducible.

Results shows that with increasing pressure on the water layer, the pressure increase in the air cushion decreases, which means that the methane emission is inhibited. It was also observed that for each of the research stages carried out, the coal taken from the 703/1 and 705/2-3 coal seams in Poland showed similar dependencies, which is why the focus was on presenting and describing the occurring effect as a general issue not referring directly to the place of sampling.

***T1.1.3 Soil gas flux measurement (baseline) at the selected PGG and Hulleras del Norte mines** (**Ineris**, IMG-PAN, PGG, HUNOSA)*

CO_2 and CH_4 flux measurements were performed with the accumulation and recirculation chamber (CARE method) of Ineris, which principle is shown in Figure 2-2, featuring a portable precision analyzer (resolution of 1 ppm).

SOIL GAS FLUX MEASUREMENT IN ANNA MINE (POLAND)

Ineris undertook two campaigns in the area of old closed Anna mine with the help of GIG for the organization and the authorization.

The most important planned action was gas flux measurements at surface above of shallowest exploitations area. For that reason, the measurements points were chosen along five transects, across the mining area, gathering points above and near the former shallow exploitations.

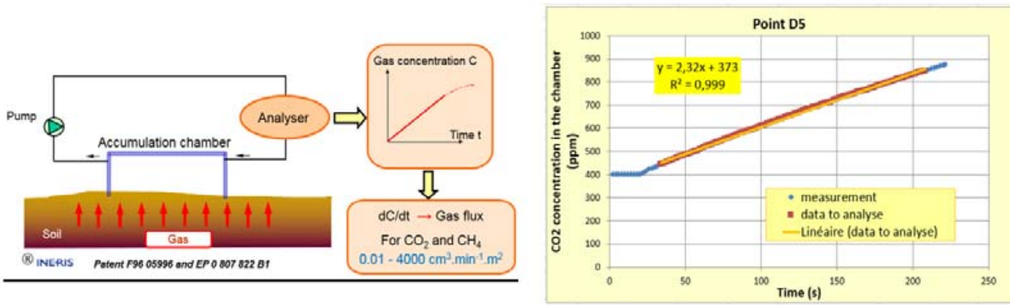


Figure 2-2. Care device: principle of gas accumulation in the chamber to measure the flux, and CO_2 flux measurement in point D5 (maximum value of summer campaign)

Altogether, 65 points were measured, which represents 11 to 15 points by profile (5 to 9 pts above the exploitation area + 6 pts outside). The position and the outline of this area was defined by PGG.

September campaign

About 20 measurements were repeated with a different temperature conditions, both above and near the shallow exploitation zone. For a large majority of measured points, there was no significant effect thermal draught on gas flux from the soil.

Additional measurements points were also carried out in a witness zone (sometimes also called reference zone), outside mining exploitations, about 2 km west. A zone with similar vegetation was chosen (forest and wild vegetation). This represents 17 CO_2 and CH_4 flux measurements.

The results showed the CH_4 flux extremely low and not measurable (< 0.01 $cm^3min^{-1}m^{-2}$), and the CO_2 fluxes were inside the normal range of natural fluxes of biological origin observed in France (3 to 25 $cm^3min^{-1}m^{-2}$). There is no anomalous flux (an anomaly would be above 25 $cm^3min^{-1}m^{-2}$).

Gas measurements were also carried out on the head of closed pits connected to the shallow exploitations area Powietrzny I, III and IV: 12 flux measurements (CO_2 and CH_4) and soil gas composition on the head or near head of closed pits. For O_2, CO_2 CO, H_2S and CH_4 concentrations in soil gas, portable multi gas detectors were used. Once again, no anomaly was observed on heads of pits for these gases.

April campaign

For this second campaign, CO_2 fluxes seem to be similar to the ones observed during the first campaign (i.e. values are inside the normal range of natural fluxes of biological origin observed in France). The CH_4 flux was extremely low and not measurable (< 0.01$cm^3min^{-1}m^{-2}$).

A more detailed examination of the two campaigns shows clear difference between summer and spring fluxes distribution: spring fluxes distribution is translated in direction of smallest values.

This seasonal evolution of CO_2 fluxes between summer and spring is typical of biogenic origin of gas (higher biogenic activity in summer than in spring).

For both of the campaigns the measured CO_2 values are inside the normal range of natural fluxes of biological origin observed in France.

Moreover, there is no anomalous CH_4 flux. The summer results are confirmed by the spring ones.

SOIL GAS FLUX MEASUREMENT IN MOSQUITERA AND PUMARABULE MINES (SPAIN)

UNIOVI undertook two measurement campaigns during the months of November 2016 and February 2017, with a similar device than the one used by Ineris. There were also optimal conditions for soil gas measurements: no strong wind, no rain, medium soil humidity.

Over Pumarabule superficial galleries (first floor is not flooded) five points were measured during the first campaign, and other five during the second.

Moreover, two measurements were made over two outcrop coal seams in the Mosquitera area. Finally, as there was a gas lighter near Pumarabule coal seams, a measurement was made there.

Not surprisingly, there were high CH_4 flows at one outcrop (3.6 $cm^3min^{-1}m^{-2}$), and at the gas lighter (21.6 $cm^3min^{-1}m^{-2}$). There was no anomalous CO_2 flow at any point.

During the second campaign, five measures were taken over Mosquitera superficial galleries that are completely flooded. At Mosquitera there were difficulties in accessing to the most relevant areas because of the mountain zone and the rough vegetation.

Results were that CH_4 fluxes were identified only above the coal outcrop or close to a gas lighter. For all the sites, the measured CO_2 values were inside the normal range of natural fluxes of biological origin observed in France.

RADON MEASUREMENTS

Parallel to CO_2 and CH_4 flux measurements also measurements of radon emission from soils and grounds in mining and post-mining areas were performed in Poland and in Spain.

In buildings located in zones affected by mining radon concentration in dwellings is usually significantly higher than in zones without influence of mining. The results of the measurements will show the pathways of radon migration and will allow assessing the radon potential of the area.

Three campaigns were conducted: in May, June, and July-September. Radon concentration in soil gas was performed with the use of a device produced by Czech company RADON and Lucas cells or/and Alphaquard radiometer. Radon exhalation was measured with the use of diffusion chambers and Lucas cells or/and Alphaquard radiometer. It can be observed that radon exhalation rate in all sites is very low, below the average value for undisturbed area (17-25 mBq/m^{2}s).

The measured values of radon concentration in soil gas are elevated in comparison with average values measured in Upper Silesia (1 000 – 20 000 Bq/m^3). In case of shaft "V Zawada" radon in soil concentrations were increasing within the distance from the centre. The shaft was sealed and gas is migrating through the pathways created around.

The pattern of the distribution of radon in soil concentration in locations of liquidated shafts is as follows: the range of measured values of the concentration of radon in soil gas changes from about 120 Bq/m^3 to about 64 400 Bq/m^3. This means that in some cases the investigated areas can be indicated as so-called areas with increased radon risk.

In 2017 measurements of indoor radon concentration in dwellings and working places located close to the monitored shafts were made. In most cases radon concentration measured in dwellings is low, below the average value for Upper Silesia – 49 Bq/m^3. In two buildings – close to shaft Jedłowniki an Utgennant Powietrzny I, radon concentration in basements are lower than on the first floor.

In Spain, a campaign was developed in April 2017. Results of radon measurement in soil gas showed that in most areas of interest radon in soil gas concertation did not exceed 10 000 Bq/m3. However, in one specific location the measured value exceeded the limits used for radon risk evaluation e.g. 34,110 Bq/m3 close to Mosquitera and Pumarabule Mines shaft location: the straight-line distance was 1.3 and 1.9 km respectively.

REFERENCE GUIDE ON SOIL GAS MONITORING IN COAL MINING REGIONS

Coal seams very often contain significant amounts of endogenous gas (mainly a mixture of CO_2 and CH_4) which can be released for a relatively long time after the end of mining operations. There is a possibility that these gases could accumulate and migrate, in significant concentration, to the surface.

First, the drivers of mine gas migration to the surface are described and explained (the rising water level within the old working, the feeding of the reservoir with gas by its release from the coal left in place, the variations of barometric pressure and the natural draft, etc.), as presented in Figure 2-3.

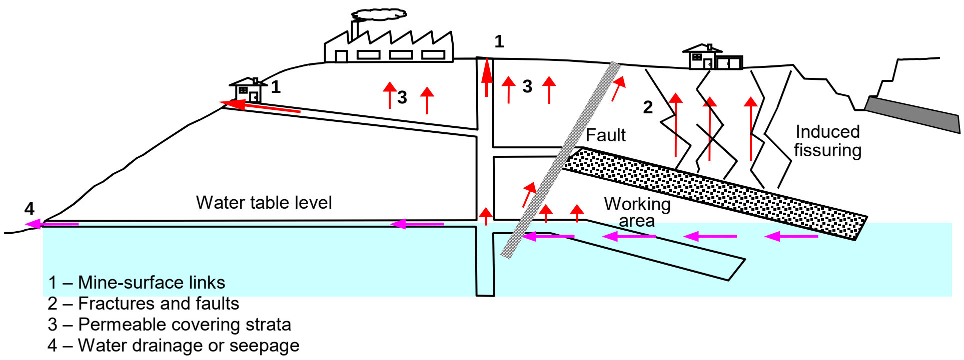


Figure 2-3. Mine gas migration paths towards the surface

(Red arrow: free gas circulation; purple arrow: dissolved gas circulation)

Threshold values are presented in Figure 2-4 (with a distinction for measurements in summer and winter conditions).

The anomaly thresholds of 30 cm^3 min^{-1} m^{-2} in summer and 12 cm^3 min^{-1} m^{-2} in winter correspond to the maximum values of CO_2 fluxes found respectively in summer and in winter, plus 10% for the maximum theoretical inaccuracy of the measurement method in the in-situ conditions.

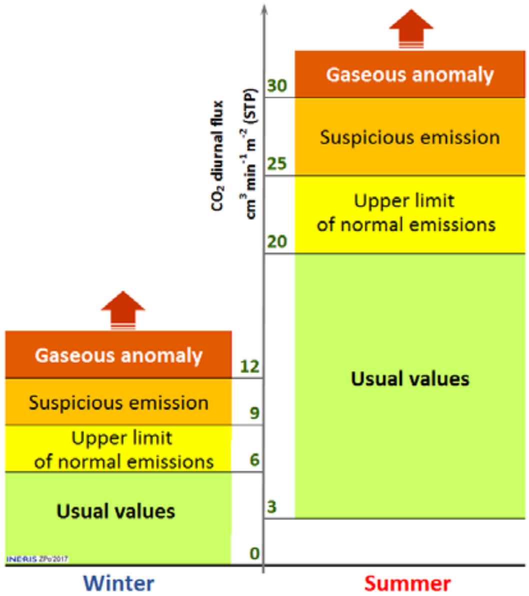


Figure 2-4. Representation of the threshold values of CO_2 flux from soils (Pokryszka, 2017)

The criteria proposed above for summer conditions can also be applied to spring and fall, especially when the meteorological conditions are similar to the summer.

Winter criteria should be applied outside of the obvious meteorological anomaly periods (e.g. excessively high temperatures lasting over one week) that could lead to a temporary increase in biological activity of the vegetation and surface soil.

Then, the field measurements performed within the project are reported and analysed.

Finally, coupled with all the local expertise previously described, the document provides detailed guidance, warnings and recommendations linked with soil gas monitoring in coal mining regions (methodology and interpretation).

The superimposition and mapping of the various data and information is carried out on a map background using a scale chosen to obtain a result that provides enough overall coverage while being sufficiently precise.

***T1.1.4 Discharged water quality measurements at the selected PGG and Hulleras del Norte mines** (**UNIOVI**, IMPERIAL, GIG, PGG, HUNOSA)*

New water quality data for the HUNOSA mine of Mosquitera in Spain, and the PGG's Rydułtowy-Anna Mining Complex in Poland, was provided to evaluate the hydrogeology and assess the surface water related environmental impacts of mine closure and post-closure.

Since August 2016, HUNOSA performed new water quality sampling campaigns, to complement the earlier sets available. The parameters measured include in situ physic-chemical measurements (pH, temperature, electrical conductivity, dissolved oxygen, atmospheric pressure) that have been measured directly, and laboratory analysis of water samples taken for total and dissolved metals, nutrients and organic carbon.

At the Polish Rydułtowy-Anna Mining Complex, GIG undertook a first surface water quality sampling campaign in 2017 for discharged water quality at different locations. In addition to this, a second underground mine water quality analysis was also carried out in 2017 in order to evaluate the temporal variability in groundwater conditions. Data from these two campaigns covered pH, conductivity, physic-chemical parameters (major cations and anions, water temperature, alkalinity) and metals.

In order to preserve important information held in the monitored data for the geochemical speciation analysis and to obtain a valid statistical interference, it was implemented an imputation method to supplement the missing and below detection limit values for the relevant parameters.

The resulting geochemical data (including the imputations) served as proxy input data, and were used in the speciation and bioavailability modelling.

T1.2 Collect historical data related with environmental incidents and risks following closure in European coal mines (led by EXETER)

Task 1.2 was aimed at reviewing within partner countries on different types of post-mining hazard (defined as "anything with the potential to cause harm") associated with both closed and abandoned coal mines that have actually caused past incidents.

These incidences generally take the form of (i) sinkholes, subsidence and shaft collapses (ii) emission of hazardous gases, and (iii) discharges of mine water.

As well as causing environmental damage, there have in some instances been loss of lives associated with specific cases.

This review consists of:

- A summary of the current "state" of the coal mining industry within country. This generally includes, where possible, some history of expansion and contraction of the industry, reasons for contraction, numbers of closed/abandoned mines etc.
- Types of post-mining hazard that have caused incidences grouped according to (a) Collapse to surface (shafts, sinkholes, subsidence, uplift) (b) Gas emissions (through shafts or strata) (c) Minewater discharges.
- A series of specific detailed case studies expanding on some of the incidences above.

A summary of some of these significant hazards that are common within the partner countries follows. These can be grouped into one of three generic categories.

SINKHOLES & SHAFT INCIDENTS

Sinkholes generally result from the collapse of workings to surface, particularly shallow room and pillar workings as well as the opening up, through collapse, of old mine shafts.

As an example of the scale of the problem, there are approximately 170,000 recorded mineshafts around the UK, 58,000 of those in urban areas.

As abandonment plans were only required to be submitted from 1872 onwards, the exact total number of abandoned shafts is unknown. Many mine shafts were crudely filled when closed and the UK Coal Authority manages about 1 000 incidents a year, many of which are shaft related (Nelson, 2013).

GAS EMISSIONS

Problems of mine gases at the surface have also been encountered. Although the techniques for reducing gas hazards before and during coal mining operations are well known in many countries, the potential post closures migration pathways for gas and the related impacts on surface are not always clearly identified.

Such pathways will occur due to cessation of ventilation at a mine, changes in barometric pressure, presence of fires underground and due to rising water levels.

The main types of gas are methane and "blackdamp" which is a CO_2 rich and O_2 deficient air and is arguably the most dangerous (Robinson, 2000). These have resulted in such incidences as explosions on surface as well as the asphyxiation of individuals.

MINEWATER DISCHARGES

Acid mine drainage (AMD) is the name given to the outflow of water from abandoned coal and metal mines that is formed by air and raising water levels in old workings reacting with sulphide minerals to form an acidic solution. As coal mines close, underground pumping of water is stopped and those mines began to flood. As water rises within the underground workings it dissolved metals and other substances, polluting rivers and streams when it reaches the surface.

This can cause incidents such as one in the UK in 2002 where a major outburst of minewater from old workings in South Yorkshire washed away a section of a main road, which had to be closed for several days. In the UK there are 141 river bodies covering 2276km that are deemed to be "at risk" from abandoned coal mines in terms of water quality (Johnston et al, 2008).

T1.3 Definition of risk criteria (UNIOVI, all partners)

Task 1.3 was aimed at providing a comprehensive report and analysis of coal mine closure risk criteria. Current environmental, ecological and human health regulatory requirements were considered and compared to historical and more recent requirements in relation to regional settings, climatic and environmental conditions.

Risk criteria were defined for every environmental risk factor considered in the project (surface deformation, air quality, ground and surface water quality) in order to set the benchmark of acceptable thresholds against which risk evaluation was carried out in MERIDA project.

Those criteria must be based on regulatory requirements when applicable and should include stakeholder's concerns, considering both risk criteria for human beings and for the environment.

RISK CRITERIA FOR SUBSIDENCE (GROUND MOVEMENT)

Mining induced ground movements are observed and measured in the mining areas for many decades. By the analysis of these measurements, the underground mining process could be correlated with the corresponding movements of the surface. Kratzsch (2002) gives a detailed overview about this topic.

For a general description and characterization of the subsidence trough, often the maximum values of the above mentioned ground movement elements are considered. Their position and size are compared with the location and parameters of the underground mine working, e.g. the longwall panel.

Important characteristics values are the so-called maximum subsidence and the angle of major influence, which determines, in conjunction with the working depth, the horizontal range of subsidence impact.

The term of maximum subsidence refers to the largest possible value of subsidence over a mine working with critical dimensions. The value of maximum subsidence depends on the values of the subsidence factor and the mining thickness. Subsidence values are usually specified in unit mm.

The mining thickness is the sum of coal and waste rock thicknesses mined out of the panel. According to RAG (2010) the mining thickness in Germany varied depending on the mining district and coal seam between 1.26 m and 3.12 m in 2009.

In case of a large underground excavation with critical dimension, the subsidence factor specifies the proportion of the mining thickness which is can be observed as subsidence at the surface. It is therefore a parameter which describes the disaggregation of the rock mass above the mining operation.

According to Preusse (1990) the subsidence factor depends mainly on the mechanical properties of the rock mass, the degree of previous working and the type and quality of the backfill. For the Ruhr district in Germany, the size of the subsidence factor is in a range of 0.65 to 0.95. In case of pneumatic stowing the values are lower, depending on the stowing quality between 0.30 and 0.50.

The so-called angle of major influence is the angle between the perpendicular on the excavation edge and the leg, which goes from the edge to the point at the surface, where the subsidence is practically zero. This "zero-subsidence-edge" of the subsidence trough separates the area of influence from the area not affected by movements.

By the determination of the angle of major influence and under consideration of the depth of mining the radius of major influence (or the radius of critical area) can be calculated.

At this point, it should be emphasized that the value of full subsidence is not the same value as the maximum of subsidence that finally occurs over any underground extraction. Full subsidence only occurs if the underground working has a critical or supercritical dimension. Especially when mining in great depth, no full subsidence on the surface occurs, because the typical size of the extraction does not reach its critical dimension.

In this case the area of mining has a so called subcritical dimension. In Germany, currently virtually all mining operations belong to the category of subcritical extractions, because after RAG (2010) the working dimensions with face lengths between 244 m and 466 m in conjunction with the common angle of major influence does not reach supercritical size.

The maximum value of tilt within the subsidence trough is located at the turning points of the subsidence curve. Therefore, two tilt maxima occur in the subsidence profile.

The curvature is concave in the subsidence border zone and convex in the inner zone of the subsidence trough. The radius of curvature is also used to describe the amount of curvature, is the reciprocal of the value of curvature.

In addition to the mentioned vertical components of ground movement, horizontal movements are described by the values of displacement, ground extension and compression. The displacement curve over a flat-lying seam extraction is in reference to the hypothesis of Avershin (1947) related to the tilt curve. It is symmetric and has in case of critical extraction dimensions maxima over the working boundaries. The displacements are directed towards the extraction area.

Changes in length, over the area of the mine working are negative and are called compressions. At the border zone of the subsidence trough ground extensions, i.e. positive change in length, occur. The transition between the extension and compression zones takes place approximately in the turning point of subsidence curve.

The ground movement components enable to describe the subsidence trough, whose shape changes depending on the underground mining activity, at any state of extraction or points in time.

On the other hand, the civil structures located in mining areas are accompanied by additional loads, stress, displacement and deformations caused by mining operations.

They were characterized with appropriate indicators. The transfer of foundation deformation interactions to the object, resulting in increased stresses, causes the created additional internal forces.

This can lead to damages of structural elements in the form of splitting, cracking with large relative displacement or other damage, such as plaster flaking, tiling damage, damages in the area of doors and windows. The first group can cause structure use safety problems or loss of functionality, while the second group leads to object deterioration and nuisance during use. Significant damage in civil structures may by caused by mining tremors and non-linear deformations in the form of fissures, vertical ground cracking, sink holes, faults, terrain drops. This type of damage requires immediate reaction in the form of quick securing of the object.

The classification of mining areas due to mining damage in Poland that closely mirrors the German methodology are the most complete of all the countries involved in this analysis. Thus, based on the comparative analysis of the deformation values measured with the values of confirmed civil structure damages, the allowed deformation ranges determined for a number of production operations under various civil structures (Budryk & Knothe, 1956) are defined. This area classification was supplemented with the deformation over time ratio (Dżegniuk & Sroka 1978) (Table 2-1).

Table 2-1. Classification of mining areas due to allowed deformation ratios

Category	T (mm/m)	R (km)	ε (mm/m)	$\dot{w}$ (mm/day)	$\dot{\varepsilon}$ (mm/m/day)	Δw (mm)
0	1.0 (0.5)	>20	0.5	1	0.005	1
I	2.5	20	1.5	3	0.015	2.5
II	5.0	12	3.0	6	0.030	5
III	10.0	6	6.0	12	0.060	10
IV	15.0	4	9.0	18	0.100	15
V	> 15.0	< 4	> 9.0	> 18	> 0.100	> 15

Where:

- *T* is the maximum tilt or maximum angular distortion, in mm/m.
- *R* is the maximum curvature radius, in km.
- *ε* is the maximum horizontal relative deformation, in mm/m.
- $\dot{w}$ is the maximum subsidence rate or subsidence velocity in vertical displacement, in mm/day.:
- $\dot{\varepsilon}$ is the maximum deformation rate or strain velocity in horizontal displacement, in mm/m/day.
- *Δw* is the subsidence evenness ratio, in mm.

For the most sensitive areas, for which none or minimum deformations are allowed, the additional "0" category was introduced (Ledwoń 1978).

The classification of areas and structures due to protection category can be the following:

- "Category 0": historical buildings, power plants, or the most sensitive areas, for which none or minimum deformations are allowed. In the case of historical buildings with load walls without reinforcing with downwards flexion the maximum allowed tilt will be of 0.5.
- "Category I": heritage buildings, industrial systems especially sensitive for human life safety or considered to be of particular importance, mostly gas distribution networks, water reservoirs, etc. There can be very minor damage, easy to repair. Area suitability for development: certain areas, not requiring structure protection.
- "Category II": more important industrial objects, large residential buildings with the length exceeding 20 m, large cities, etc.. There can be minor damage, relatively easy to repair. Area suitability for development: areas for which partial protection of all structures is not profitable.
- "Category III": main roads, small railway stations and routes, industrial buildings less sensitive to ground movement, smaller residential buildings (10–20 m in the horizontal projection), municipal treatment plants, etc.. Area suitability for development: areas requiring partial protection of structures (the type of protection depends on the type of the civil structure, its sensitivity, ground conditions, degree of deformation).
- "Category IV": storehouses, small (individual) residential buildings, other less important structures. Possible very serious damage, with a risk of destruction. Area suitability for development: areas requiring significant protection of the structures.
- "Category V": very serious damage and destruction of civil structures, as well as areas with a high probability of non-linear ground movements (sink holes, large crevices, etc.). Area suitability for development: areas unfit for construction development.

Finally, to precisely but nevertheless quickly evaluate and classify building objects, especially in the heavily populated mining areas of Europe with a large number of objects influenced by mining, Grün (1998) and others defined and incorporated characteristic object attributes to an assessment system for object classification. The total sum of points is the basis of building classification into the correct resistance category, and both in Poland and in Germany the same methodology is used.

RISK CRITERIA FOR WATER QUALITY

In the case of water quality, most of the risk criteria are usually parameters defining the quality of the water body where effluents are discharged. Such criteria are quite homogeneous due to the common legal context set by the Water Framework Directive (WFD) and its Daughter Directives.

The WFD requires surface water bodies to be classified according to their ecological status classes and their chemical status classes. The quality element with the lowest (worst) status for a water body determines the overall ecological status. The different elements for the definition of each status are those established in the WFD.

The Freshwater Fish Directive defines a collection of parameters to guarantee the quality of running or standing fresh waters that support fish life. It identifies two categories of water (those suitable for salmonid fish and those for cyprinid fish) and distinguishes the 'Imperative Standards' from 'Guideline Standards'.

Meanwhile, the Priority Substances Daughter Directive defines environmental quality standards (annual average and maximum allowable concentration) for priority substances and certain other pollutants.

The values for those standards are common to all Member States and, in principle, any water body where mine water is discharged should comply with them.

Going further, some Member States, such as the UK, are proposing particular recommendations on environmental standards and conditions that are type-specific (different water types will have different standards).

"Lowland" means less than or equal to 80 metres above mean sea level. In general, the new proposed standards are more specific and thus appropriate to guarantee the quality of water, but they are not always tighter.

Regarding the presence of metals, the Freshwater Fish Directive defines limit concentration values of total zinc and dissolved copper for different water hardness bands. Nevertheless, it is generally accepted that they do not accurately represent the bioavailable metal fraction.

Thus, the UK suggests considering the metal bioavailability and adopting a tiered, risk-based approach, as a single value for an EU-wide metal environmental quality standard.

Additionally, the revised Priority Substances Daughter Directive adopts as well this approach to define the environmental quality standards for lead and nickel.

Together with the existing annual average standard, the UK proposes Predicted No Effect Concentration (PNEC) standards for some other relevant metals that could also be implemented.

According to the quality standards defined for the receiving water body, the competent authority may establish case-specific limits and/or monitoring measures for the quality and quantity of the mine water discharge. Such is the case of Spain and Germany.

On the other hand, the Czech Republic and Poland have a second approach for the definition of risk criteria concerning surface water quality. Both Member States have established admissible levels for certain pollutants in the discharged water. In the case of the Czech Republic, those levels are defined for different industries, including "Coal and lignite production and processing" and "Ore extraction and processing". In the case of Poland, they are defined as threshold limit values for water contaminants from industry including water from coal mine drainage.

The parameters that have been identified as relevant to assess the surface water environmental impacts in the case studies included in this project are the following:

- For the water bodies: pH, SPM, Al, Cu, Zn, Pb, Ni.
- For the discharged water: pH, TDS, DOC, SO_4, Si, Cu, Mn, Zn, Pb.

Summarising the different criteria established by those partners who have defined admissible levels in the discharged water, the limits selected for the relevant pollutants would be those recorded in Table 2-2.

Table 2-2. Limit values for the relevant pollutants in the discharged water

	Limit value
pH	6.5 - 9
TDS (mg l^{-1})	35
DOC (mg l^{-1})	30
SO_4 (mg l^{-1})	500
Si (mg l^{-1})	Not defined
Cu (mg l^{-1})	0.5
Mn (mg l^{-1})	1
Zn (mg l^{-1})	0.5
Pb (mg l^{-1})	0.5

Similarly, the WFD and the Groundwater Daughter Directive establish the European common legal context for groundwater quality.

Groundwater quality status is required to take account of the particular rivers' and wetlands' needs that depend on groundwater, the other uses of the groundwater body, as well as its general overall quality, so the classification of groundwater must reflect the unique features of each groundwater body.

Nevertheless, specific standards have been defined in different Member States, such as the United Kingdom and France, for substances that have been formally identified as hazardous.

The tighter of those standards should be adopted in cases where groundwater bodies are affected.

Finally, in case the water is intended for human consumption, the specific quality standards and pollutant concentration limits defined by each Member State should be taken into account.

RISK CRITERIA FOR GASES

The regulations in Europe about air quality refer to requirements regarding only operative mines and air quality inside the mines.

Something similar happens with radon 222, which has no limit concentrations. The exposure to radiation is governed by the rules of radiation protection, something valid for the entire industry.

On the other hand, when integrated pollution control takes place within the area of a mine, authorities have usually powers to limit the emissions of some processes, but this control of air pollution is completely discretional without specific emission levels to be applied.

Only Poland has a criterion of safety in hard coal mines which are closed, taking into account the amount of methane in the mine workings.

T1.4 Setup and development of the GIS data management and visualisation tool (DMT, *IMPERIAL**)***

As a result of the task 1.4. an initial version of the ArcGIS spatial data management server and client and visualization tool was made.

The spatial data management and visualization tool was set up in a virtualized UNIX environment running at DMTs datacenter. The web-application framework developed for MERIDA based on three core components:

GEO-DATA PROVIDER

GeoServer is an open-source server written in Java that allows users to share, process and edit geospatial data. It operates as a node within a spatial data infrastructure, designed for interoperability.

It supports efficient publishing of geospatial data from any major spatial data source using standard protocols like KML, GML, Shapefile, GeoRSS, PDF, GeoJSON, JPEG, PNG and more.

WFS transactional profile (WFS-T) is also supported, which permits the actual sharing and editing of the vector data that is used to generate the maps.

DATABASE

The DB-backend consist of a PostgreSQL database with enabled PostGIS extention. PostGIS is a spatial database extender for PostgreSQL object-relational database.

It adds support for geographic objects allowing location queries to be run in SQL.

To the already existing basic geometry types, PostGIS adds additional geospatial types and functions which make handling spatial data in the database easier and more powerful.

It is an integrated set of functions and procedures that enables spatial data to be stored, accessed, and analyzed quickly and efficiently in an SQL database.

WEBSERVER

For accessing and managing the web-frontend, Nginx is used as a webserver, reverse-proxy and load-balancer.

Nginx is deployed to serve dynamic HTTP content on the network using FastCGI and SCGI handlers for scripts. It uses an asynchronous event-driven approach to handling requests with a modular architecture.

This method provides more predictable performance under high loads.

The WebGIS-Application is developed as a client framework for spatial data infrastructures.

The software is implemented in JavaScript and Node.js and built upon Ext JS and OpenLayers.

2.3.2 WORK PACKAGE 2: DEVELOPMENT OF ENVIRONMENTAL IMPACT ASSESSMENT MODELS FOR COAL MINE CLOSURE AND POST-CLOSURE PERIODS

T2.1 Development and validation of detailed models to assess the effects of subsidence and demonstrate their implementation at the selected PGG and HUNOSA mines (IMG-PAN, *GIG, PGG, HUNOSA**)***

The aim of this task was to create a suitable model, which would allow to properly describe the behaviour of rock mass in the region of flooded coal mines. The presented models include not only the behaviour of flooded fractured rock mass but also represent the possible surface deformation.

Regarding HUNOSA mines, due to the absence of ground movement measures in the Mosquitera and Pumarabule Mines, the work was carried out at Candín mine, where ground movement measures were taken and thus it was possible to validate the model.

ANNA MINE (POLAND)

Numerical modelling of geomechanical phenomena occurring in the rock mass disturbed with mining operations means considering a number of geological factors like lithology, tectonic structure and mechanical properties of rocks.

Preparing a physical model of the rock mass, we create its idealised physical system, which, for the needs of the analysed process, will represent the actual system and its basic qualities.

In the case of Anna mine, a final 13-layer model was developed for numerical modelling purpose. The advantage of the 13-layer model is the ease to implement it for numerical modelling processes associated with flooding mines, and, at the same time, its high correlation with the actual rock mass.

In addition to the physical-mechanical parameters of the rock mass, another important thing in numerical modelling of mining activity is the height of the cave-in zone.

Using prepared earlier information, the 3D numerical model using Finite Element Method, which represents the analyzed region of the mine, has been prepared.

When building a numerical model, it must consist of a sufficiently large number of elements, in order to ensure high accuracy and quality of results from calculations.

Generated model for Anna mine, with flooding zones marked in red is shown in Figure 2-5.

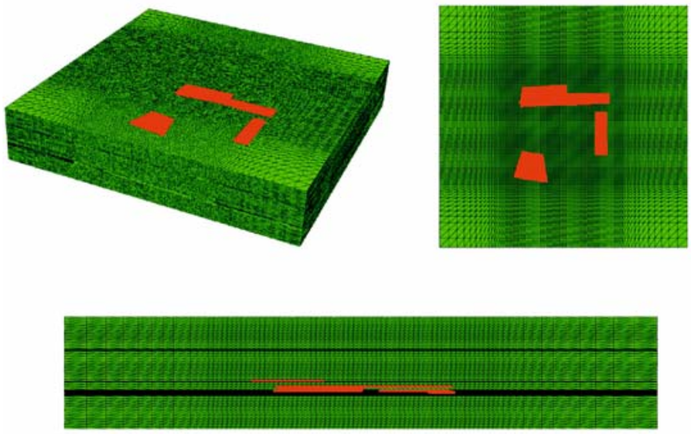


Figure 2-5. Generated model for Anna mine, with flooding zones marked in red

It is necessary to apply appropriate boundary conditions, i.e. displacement conditions of the model walls, gravity load, and application of pressure resulting from the initial state of stress and strain.

Numerical calculations were performed for the constructed three-dimensional model in the following calculation steps: (a) simulation of the initial state of stress and strain, (b) longwall panel exploitation, where the so-called equivalent elements with lower parameter values in a highly disturbed zone (a cave-in zone) were introduced into the model, and (c) goaf flooding simulation. The selected simulation was related to the change in the volumetric weight of the rock mass in the area of the mining goafs.

The results of the models allow to obtain the distribution of deformation indicators and stresses on the ground surface. In addition, the distribution of these indicators in the rock mass can be achieved.

The first step in numerical calculations was to recreate the initial state of stress and strain in rock mass in the flooding mine area.

The second step of simulation was to perform simulation of mining activities. In case of Anna mine, the excavation with roof collapse has been performed.
Simulation of seam exploitation has been modelled using equivalent elements with lowered physical-mechanical parameters applied into the cave-in zone. In this place, the model is also calibrated based on geodetic measurements performed on the ground surface.

For this purpose, the "back analysis" method is used, which is based on matching the results from modelling to real measurements. In this way, the final parameters of the rock layers are obtained.

In the last step, the flooding of the mine is simulated. The calculation has been performed using medium's density change method proposed by the authors.

Changing density of the material in excavation region, expansion of cave-in zone is achieved and the propagation of the vertical displacement from this zone up to the surface.

The distribution of the ground surface deformation and rock mass deformation is obtained (Figure 2-6).

Figure 2-7 shows the change in vertical displacements on the ground surface and in the rock mass for post-mining state (a) and after flooding of goafs (b), respectively.

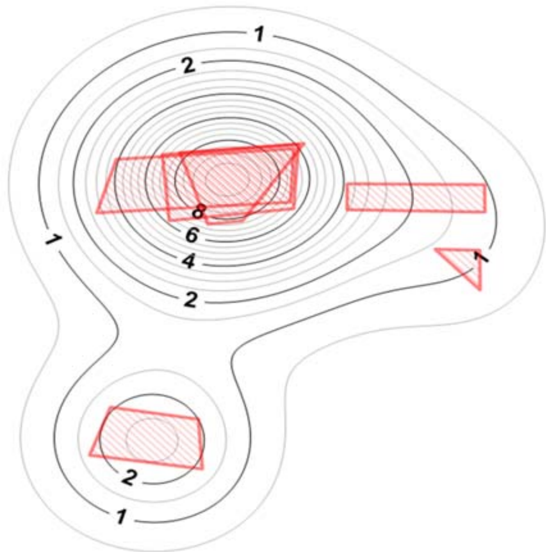


Figure 2-6. Distribution of the ground surface deformation and rock mass deformation (mm)

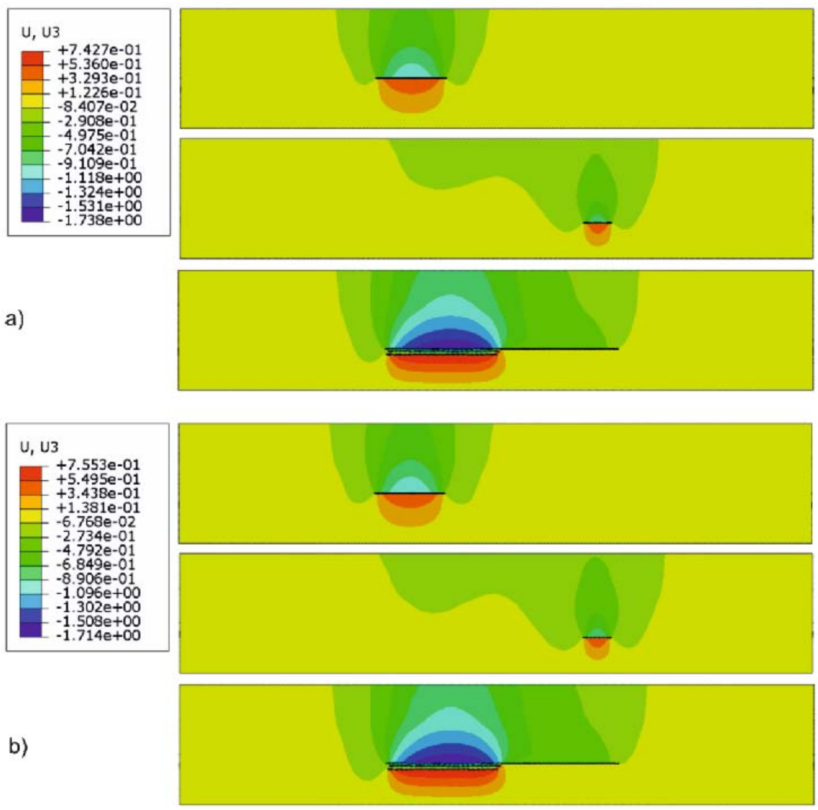


Figure 2-7. Vertical view of the changes in vertical displacements (mm) on the ground surface and in the rock mass for post-mining state (a) and after flooding of goafs (b)

CANDÍN MINE (SPAIN)

During the implementation of the project, the analyses of the flooding of underground excavations have been performed using three new methods, which were: (a) pore pressure change method, (b) hydrostatic pressure change method, and (c) mediums density change method.

Performing number of analyses using above mentioned methods, which confirmed the possibility of modelling the phenomenon of uplift of the ground surface as a result of the flooding of underground excavations, the authors have proposed mediums density change method to proper calculations.

This method is based on the principles of classical soil mechanics and takes account of the impact of water on the volumetric weight of soil. Depending on the height of the groundwater table, two approaches to determining the mass of the rock mass are distinguished.

Numerical modelling of geomechanical phenomena occurring in the rock mass disturbed with mining operations means considering a number of geological factors like lithology, tectonic structure and mechanical properties of rocks.

Preparing a physical model of the rock mass, an idealised physical system was created, which, for the needs of the analysed process, represents the actual system and its basic qualities. In the case of Candin mine, due to the complex geology of the rock mass and the limitations of the calculation program, FEM simulation has been performed for homogeneous model.

The first part of the work concerned the characteristics of the Candín mine and the method of extraction of the steeply inclined seams. The analysis of the obtained materials shows that due to geological conditions, the mine has been extracting seams with a large angle in the range of 50 to 85º.

As a result of these works, there is an infraction of the initial state of stress and strain of the rock mass, which results in the formation of disturbed zones (fracture and caved zones).

Due to the fact that the area of the mine is very large (approx. 5 985 million m^3), which in numerical modelling is directly associated with the necessity to use a tremendous number of elements, this prevents the performance of credible modelling analyses to a large extent.

That is why in order to perform precise numerical simulation, a decision was made to divide the whole region into four parts (A, B, C and D) (Figure 2-8) where for the neighbouring regions the calculated deformations as the boundary conditions were added.

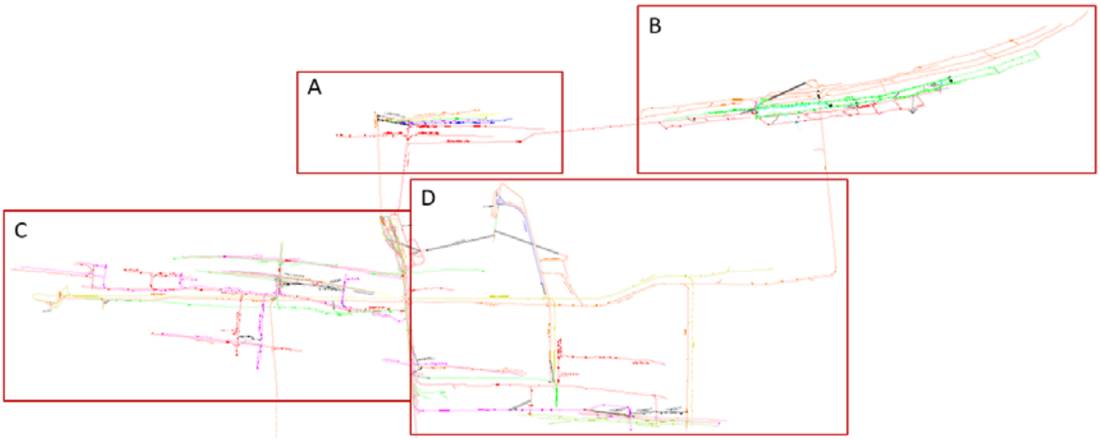


Figure 2-8: A map of seams exploited in the Candín Mine belonging to HUNOSA

From the analysis of the literature, the authors also have presented methods for modelling the impact of extraction of inclined seams on the ground surface.

Geometric-integral solutions have been presented, which were most popular in the calculation of surface deformation. This is the SEH method and the Knothe method. Whereby the second method is the most commonly used to model these types of issues.

In the calculations presented, the authors used a program based on Knothe's theory. The works carried out by Sroka and Niedojadło on the deviation of the subsidence basin were also used for calculations. The solution proposed by these authors assumes the division of mining extraction area into finite elements and then the preformation of the numerical calculations and summing up the results. The calculations showed, that on the modelled ground surface area an asymmetrical subsidence trough is obtained, and for specific conditions (appropriate depth of operation, inclination, etc.) two subsidence troughs are obtained.

Then, based on the obtained data, the impact of the flooding of Candín mine on the ground surface has been performed. The first step was to perform calibration of the numerical model to match the results of calculations with the results of surveying measurements. For this purpose, the authors decided to use one of the theories of calculating ground surface subsidence for extracted inclined coal seams (Sroka & Niedojadło, 1978).

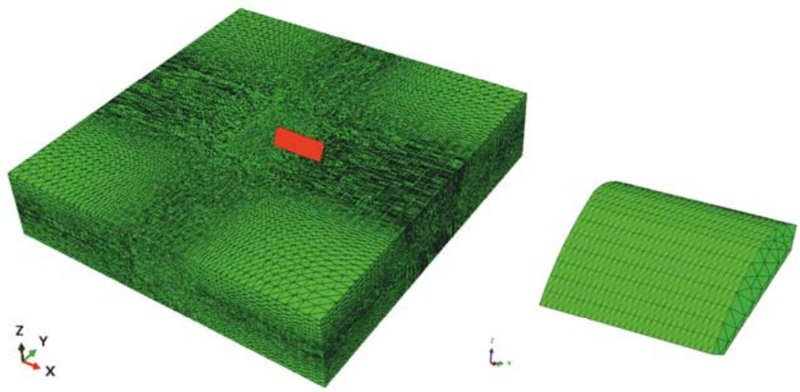
The next step of the performed analyses involved the preparation of ground surface displacement maps for states after extraction and after flooding the mine, based on the produced results and using numerical calculations. The produced results were summed up according to the superposition principle.

Then, the numerical calculations using the finite element method were performed. The problem of modelling the numerical deformation of the ground surface area for flooded coal mines characterized by a steep inclination of the seams has been omitted in the world literature, so far.

The construction of the numerical model describing this problem is the first such solution for the time being. As in the case of Anna mine, the simulation of mine flooding was carried out by the method of changing the bulk density of the rock mass in the caved zone.

As has been mentioned earlier due to the vast area of Candín mine, it was decided to divide it into four regions. The calibration of the model was carried out for region A, due to geodetic measurements performed in this area. The information was necessary to determine the physical and mechanical parameters of the rock mass (Figure 2-9).

Using the obtained rock mass parameters numerical calculations for the remaining three regions have been performed. As in previous cases, the models were built of eight-node elements in a three-axis state of stress.



(a) (b)

Figure 2-9: A numerical model for region A of the Candín Mine: a) the entire model with an indicated extraction zone, b) a parcel undergoing extraction, along with the cave-in zone

Each of the walls modelled in the investigated regions of the mine was positioned at an angle falling within a range of 50-85º from the horizontal. Just like in the case of region A, simulations were performed in three steps of calculations, i.e. simulation of the initial state of stress and strain, followed by coal extraction with roof collapse and then by flooding the mine as a final step.

Because of the performed numerical analyses, changes in the displacement of the ground surface in the form of subsidence and uplift were established.

Figure 2-10 presents in sequence the change in vertical displacements before and after mine goaf flooding for the remaining regions (regions B, C and D).

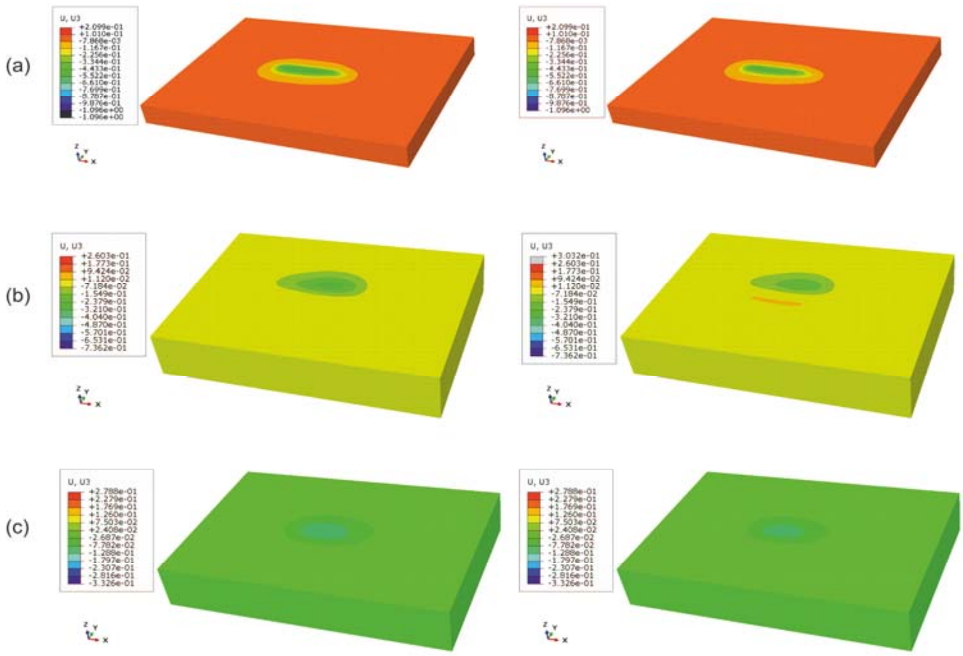


Figure 2-10: Successive maps of vertical displacements (mm) for states before and after flooding for: a) region B, b) region C, c) region D

The next step of the performed analyses involved the preparation of ground surface displacement maps for states after extraction and after flooding the mine, based on the produced results and using numerical calculations. The produced results were summed up according to the superposition principle, as presented in Figure 2-11.

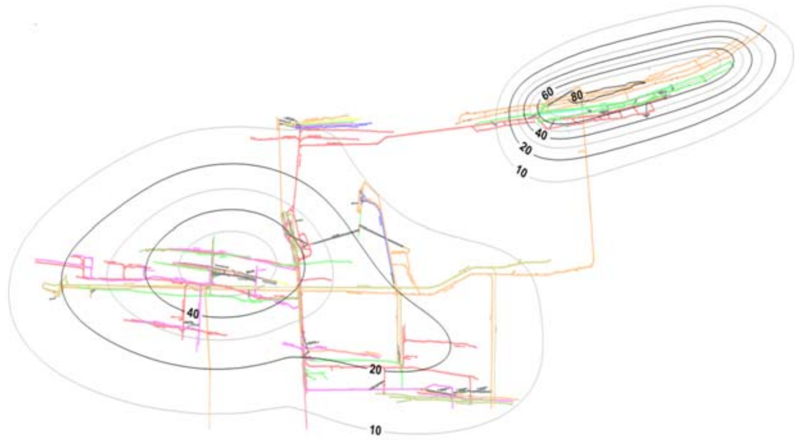


Figure 2-11. Distribution of the ground surface deformation and rock mass deformation (mm)

T2.2 Development and validation of detailed models to assess the groundwater pollution impacts and demonstrate their implementation at the selected PGG and HUNOSA mines (UNIOVI, GIG, IMPERIAL,** HUNOSA, PGG**)

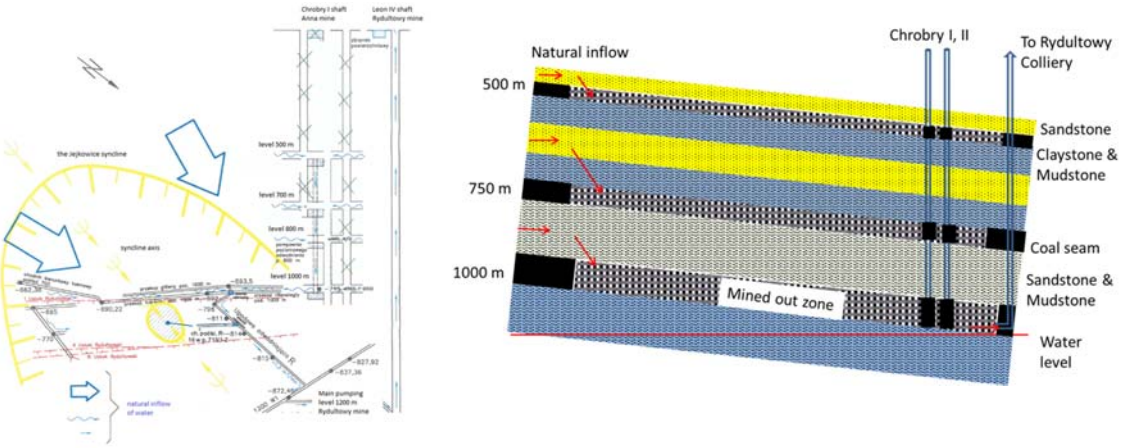
The aim of this task was to use hydrological modelling software to simulate groundwater flow and solute transport at the selected PGG and HUNOSA mines.

Other aims were: to validate and assess modelling results, to consider modelling uncertainty given historical and newly collected monitoring data, and to identify the structures/receptors at risk and evaluate the environmental risk exposure.

RYDUŁTOWY-ANNA MINING COMPLEX (POLAND)

At Anna mine, mining operations were conducted in region R until abandonment in 2015. The Rydultowy mine is divided into two parts: Northern and Southern. The Southern part consists of two regions, i.e. E1 and W1, which are actively mined.

A conceptual model aimed at describing the natural inflows at the Rydułtowy-Anna Mining Complex was developed. Since the natural inflows at 4 different mining levels for Anna mine are collected and transported through shaft Chrobry I to level 1,000 m, which is then taken away via gallery I-1200-W1 (coal seam 713/1-2 level 1,200 m) in Rydultowy mine, the conceptual groundwater flow model for the mine area of interest covers Rydułtowy-Anna Mining Complex (Figure 2-12a and b). In order to represent the groundwater system effectively and perform risk assessment in Task 3.2, the initial model domain was later extended to include the southern part of Rydultowy mine, in addition to the region R of Anna mine.



(a) (b)

Figure 2-12: a) Scheme of main drainage system from the Chrobry I shaft ((Anna Colliery, region R) to the Leon IV shaft (Rydultowy Colliery), and b) the conceptual groundwater flow model for the mining area of interest, showing the shafts at Anna-Rydultowy mining complex

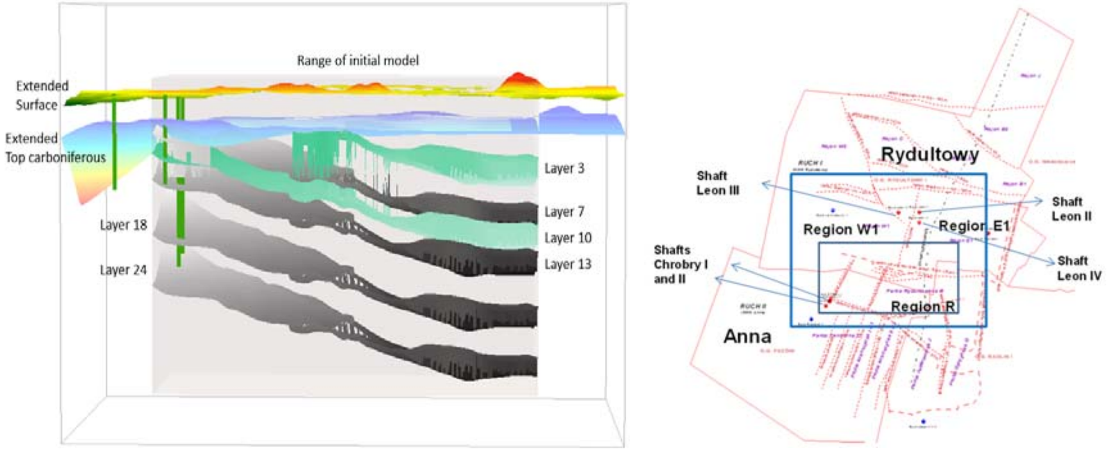
Flow rates for both mines, were used to develop the conceptual model and validate the numerical model. The inflow rate for Anna mine is found to remain largely constant at about 1.3 m^3/min up to 2010, and then it declined gradually to ~ 0.8 m^3/min by 2016. The level at 500 m has the lowest inflow rate, whereas level 700 m has the highest. The Rydultowy flow rate is much higher at ~ 2.2 m^3/min, reflecting the fact that it is an active mine.

In addition to the groundwater flow system, the geology, hydrogeology and the topography of the area is also included in the model. A 25-layer stratigraphy at the Anna Colliery (Region R) was used to create the 10-layer simplified model stratigraphy for both mines.

The mined-out zones at >900 m depth are immediately overlain by the sandstone & mudstone formations, which is likely to be source of the natural inflow collected at the mine level 1,000 m. Based upon the horizons corresponding to the initial model reported previously and the surface topography, new horizons for the extended domain were created by the researchers at Imperial College to be used for the construction of the extended groundwater model (Figure 2-13a and b).

FEFLOW, a Finite Element subsurface flow and transport model, was used for the development of the numerical model. The elevation data for each of the layers were extracted from the Digital Elevation Model for the deeper horizon and the remaining stratigraphy in the model region was calculated based on the thickness and depth of each top layer.

These were used as the basis for the regionalisation of elevations for all layers. The full implementation represents the complete 3D groundwater system in the model developed. The two shallowest layers in the numerical groundwater model are formed by combining the top 10 layers in the 25-layer stratigraphy.



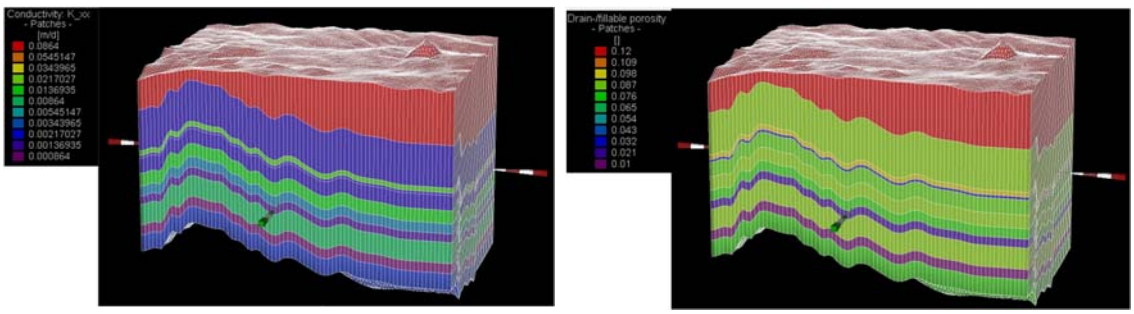
(a) (b)

Figure 2-13: a) A 3D profile of the model and horizons, and b) the extended domain for the 3D ground water model superimposed on the mine layout map

The extended model domain measures 5.25 km x 4.1 km. The groundwater model was then attributed with hydraulic properties, i.e. hydraulic conductivity and specific yield, obtained from the literature and considering the impact of coal extraction and caving on the overlying strata.

Next, material properties, such as hydraulic properties of water-bearing sandstones and mudstones at different depths (open porosity, specific yield and permeability) were assigned. These are considered to show a marked downward trend with depth. The results of laboratory and field investigations indicate that Carboniferous sandstones and mudstones below the depth of 700 – 800m are practically impermeable. However, in the areas of mining, where displacements, fractures and de-stressing of rocks accompanying mining excavation took place, rock permeability is increased.

Hydraulic conductivity from 2-100 10-8 m/s)/(mD) and specific yield from 0.02-0.12 were attributed at different layers, taking into account the impact of coal extraction and caving on the overlying strata (Figure 2-14). However, adjustments have been made for the areas of mined out coal seams, with much higher values for both parameters (100-200 10-8 m/s/mD and 0.13-0.15, respectively). The impact of caving and fracturing on the permeability of the overlying strata is reflected in the values of vertical to horizontal hydraulic conductivity ratio, ranging from 0.1 to 0.5.

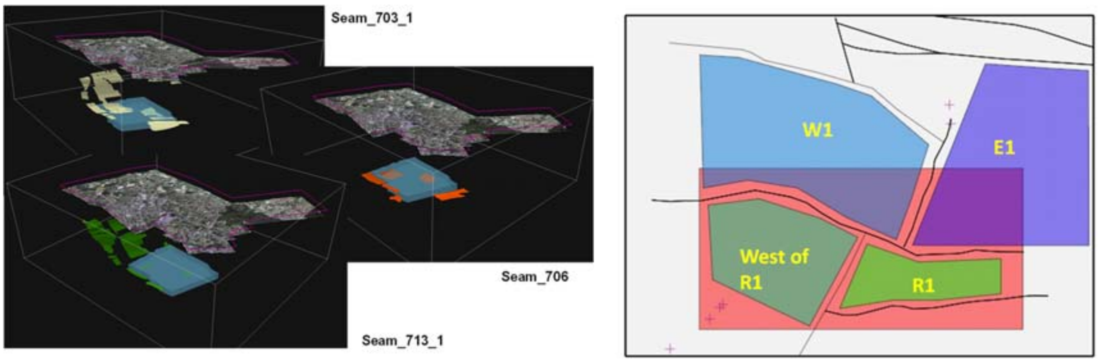


(a) (b)

Figure 2-14: 10-layer 3D groundwater implemented in FEFLOW 7.0. a) Hydraulic conductivity Kxx (m/d), and b) specific yield (frac.)

In terms of boundary conditions in the groundwater model, fixed hydraulic head at western and eastern boundaries are considered to represent the current conditions in the mining area, and also provide the main sources for the mine natural inflow. The model was subsequently calibrated using the latest mine inflow data.

Figure 2-15a presents the mined longwall panels in seams 703_1, 706 and 713_1 in Rydultowy mine. Four mining regions were considered: W1 and E1 in Rydultowy mine, and R1 and the region to the west in Anna mine (Figure 2-15b).



(a) (b)

Figure 2-15: Snap shots of mined out longwall panels in individual seams

To simulate mine inflows, sinks are created in the three coal seams in the model, to which reduced hydraulic heads (~1m) are assigned.

In order to calibrate the model, it was run in steady-state mode during simulations. The hydraulic heads at the western and eastern boundaries were adjusted so that the sum of the simulated outflows match the inflow rates recorded at the two mines. It was found that a fixed hydraulic head of 130 m and 280 m at the western and eastern boundary respectively yields a satisfactory match. As shown in Table 2-3 a good match was obtained for Anna mine. Considering that there are other active mining regions, in addition to W1 and E1, in Rydultowy mine, the simulated flow rates were slightly lower than the field data. The natural inflow into the different levels is affected by a number of factors, including the depth, the conductivity overlying strata, and lapse of time after caving (consolidation). The hydraulic head distribution at three different mine levels is illustrated in Figure 2-16.

Table 2-3. Results of simulated mine inflows compared to the field data at the two mines

Inflow rate, m^3/min (m^3/day)				Simulated, m^3/day			
Rydultowy (First half 2018)		Anna (2017)		Rydultowy (First half 2018)		Anna (2017)	
				E1	W1	R1	West of R1
Level 400m	0.650	Level 500m	0.133	1,571	1,055	7,32	453
Level 600m	0.423	Level 700m	0.297				
Level 800m	0.477	Level 800m	0.183				
Level 1,200m	0.403	Level 1,000m	0.2				
Total	1.953 (2,812)	Total	0.813 (1,171)	2,622		1,185	

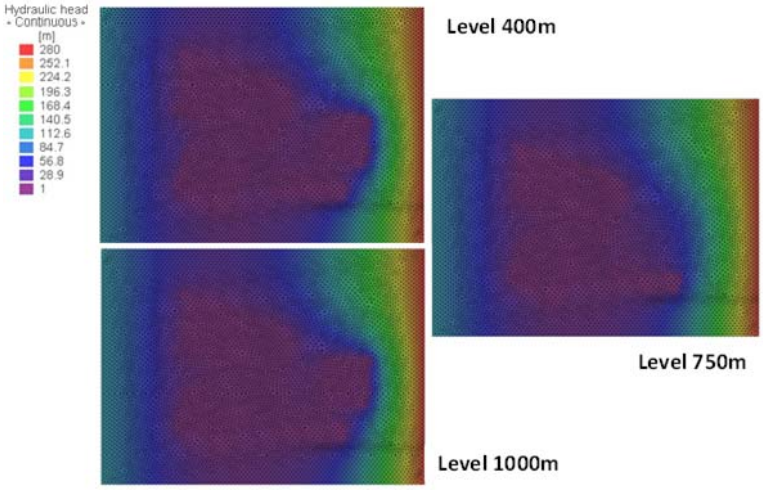
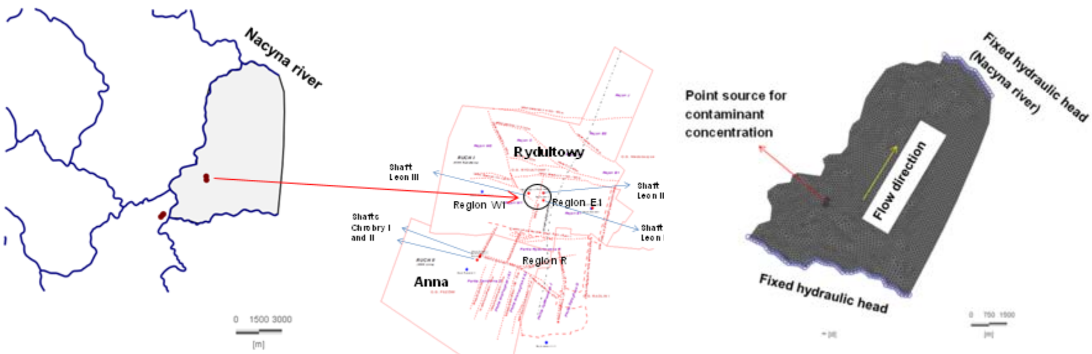


Figure 2-16. Hydraulic head distribution at three different levels

Dewatering of closed mines is expected to continue, as many of the Upper Silesian Coal Basin mines are connected by a complex system of galleries. This will lead to the quantity of mine water carried away to rivers that is not decreasing significantly. However, when the cessation of dewatering occurs, some parts of the region below ground will be flooded by rising groundwater. It may occur in areas where shallow water-bearing layers are not isolated from the carboniferous rock mass.

Considering that risk for groundwater pollution around these deep mines would only be the case when the Rydultowy mine also closes down, and the water table rebounds when the pumping is terminated. In view of the thin surface aquifer (~10m thick) at the top, which is underlain by an aquitard of ~260m thickness, the only contact between the rebound groundwater and the thin surface aquifer would be around the abandoned shafts, Therefore, a surface aquifer model was developed for groundwater flow and contaminant transport modelling through a reactive multispecies coupling, for risk assessment.

This involved integration of the regional watershed around the mines in the model and focusing on the sub-region (marked R in Figure 2-17a), which boards Nacyna river to the North. This sub-region contains three shafts (Leon II, III and IV) in Rydultowy mine (Figure 2-17), which are considered as potential sources of mine water seepage into the surface aquifer when the Rydultowy mine is also abandoned in the future and pumping in the complex is terminated.



(a) (b)

Figure 2-17. (a) Schematic of regional watersheds and the location of Anna and Rydultowy mine shafts, and (b) model domain for groundwater and contaminant transport modelling, with the Rydultowy mine shafts considered as potential sources for surface water contamination

MOSQUITERA AND PUMARABULE MINES (SPAIN)

The conceptual model of the Mosquitera and Pumarabule Mines area has been developed with the purpose of constructing a relevant numerical model. With the information available, classified and organized in the hydrogeological knowledge base, a discussion and analysis has been conducted to define what the conceptual model should contain (Anderson et al., 2015).

As main premise the model must include the extension of the mine workings of the mines and the surrounding massif.

However, to build the numerical model, the total volume has to be delimited identifying hydraulic limits where an appropriate boundary condition is applied.

The lateral extension of the model is constraint by geological features, water divides and unaltered massif between mines with no direct connection. The main settings controlling the extension of the model are faults and impervious levels in the stratigraphic sequence. The lateral extensions of the model are presented in Figure 2-18.

The depth of the model is also considered by means of geological settings and regional water flow.

The model assumes that the mine workings act as an extensive network of drains that collects the water from precipitation recharge. The water infiltrates from the surface and flows through the massif to reach the open voids of the mine.

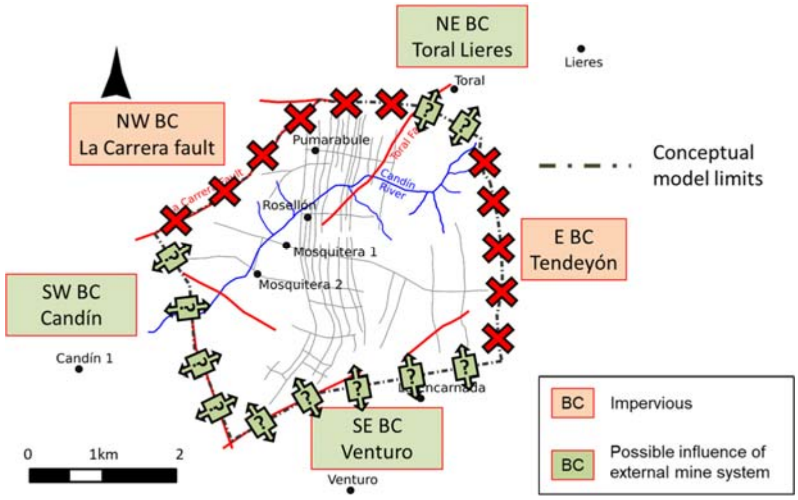


Figure 2-18. Extension of the conceptual model

Because the height of the water level in the mine must be maintained with artificial pumping, water flows by the galleries to the shafts where is extracted and discharged to the surface. Figure 2-19 shows a schematic cross-section showing the assumption of flow directions in the model.

Using precipitation data (from Oviedo station, located about 15 km from the study area) and infiltration hypothesis, the total balance in Mosquitera and Pumarabule Mines has been estimated. Previous authors (Ordoñez et al., 2010, Muñoz, 2015) have suggested that the total of infiltration in the Mosquitera and Pumarabule Mines area ranges between 22 and 26% of the effective rain. The dewatering points of the model are the pumping facilities located in Mosquitera and Pumarabule Mines.

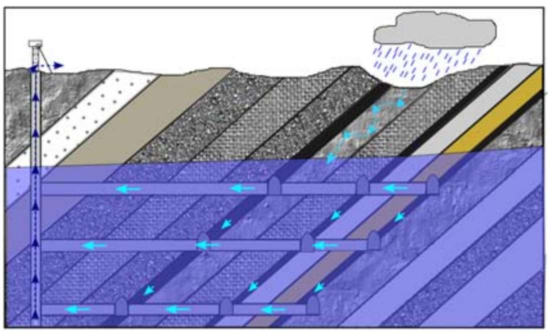


Figure 2-19. Conceptual scheme showing main flow directions assumed in the model

After water rebound five pumps were installed in Mosquitera 1 (three pumps) and Pumarabule (two pumps) with the objective of keep levels below a previously determined security height placed at an elevation of 230 m.a.s.l. This height was later updated and raised to 235 m.a.s.l.

An analysis of pumping rates was conducted to estimate mean, maximum and minimum discharges.

There have been identified main water balance terms and characteristics of the boundaries.

The domain and the elements defined are translated into the numerical model to be parametrized and governing equations assigned.

The next step was to develop the numerical model. The numerical model is expected to include discrete elements that represent the mine workings such as galleries, shafts and working exploitation planes embedded in a massif where porous media flow takes place. The vertical shaft allows access to levels that connect with the coal exploitation zones with galleries. These elements represent important water flow and chemical transport paths that must be considered (Figure 2-20).

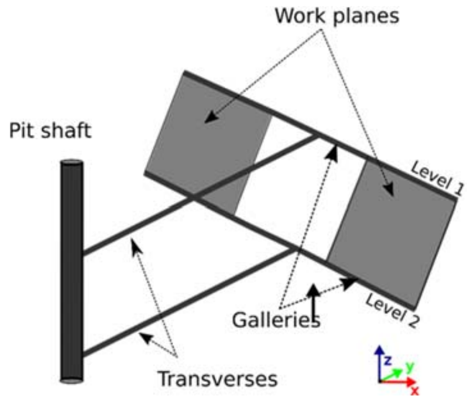


Figure 2-20. Schematic representation of some elements of the mine to be included in the numerical model

The physical laws that govern water flow in the elements of the mine are different. Two main processes must be coupled, but assuring continuity and conservation of mass: free water flow in the mine workings and porous media flow in the massif and filled working zones.

A geochemical transport model has been coupled to the flow model to evaluate the concentration of species at the shaft (discharge point) (Figure 2-21).

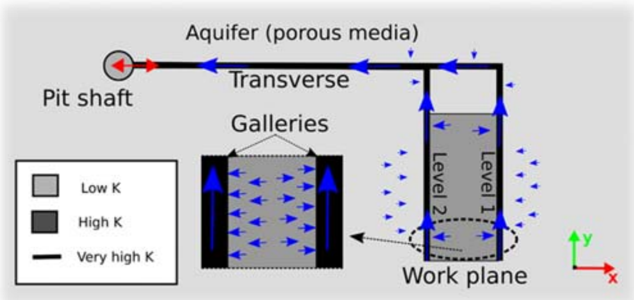


Figure 2-21. Plain view showing main processes taking place and to be modelled

As a previous step to the fully implementation of the real mine and the study area in the numerical software, COMSOL Multiphysics, the elements and physics involved in synthetic numerical models were studied. These models aim to study the capabilities of the simulator in a similar mine type geometry with similar processes and the same physical laws applied (Figure 2-22).

Underground mine workings represent a complex geometry that cannot be directly implemented into the numerical simulator from the original mine plans.

Surfaces representing working plans were joined to one-dimensional elements that represent galleries and shafts to form the complete network of mine voids.

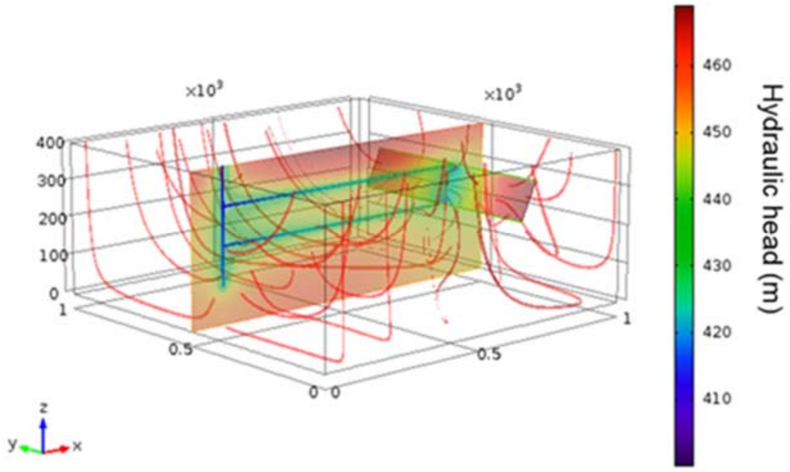


Figure 2-22. Example results of the synthetic model for groundwater in Spain

The construction of the final model requires the definition of a volume limited by the boundaries defined in the conceptualization stage. This is the volume in which the mine geometry is embedded and where porous media flow will take place. The building of this volume was conducted using AutoCAD and COMSOL (Figure 2-23).

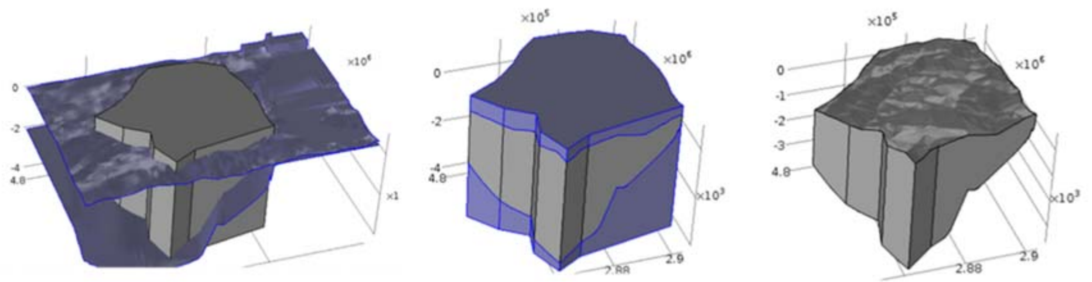


Figure 2-23. Construction of the model volume by clipping of boundaries for Mosquitera and Pumarabule Mines

After, the mine workings including planes and galleries are merged with the volume to obtain the final geometry that will be utilized in the numerical model. Then, parameters are assigned to the domains and the model can be meshed for running and extractions of results.

The results of the models allow to obtain the spatial distribution of hydraulic variables of interest such as hydraulic heads, water velocities, discharges or flow regime in the mine open voids. First, the influence of the mine is shown in the depression of hydraulic heads near the workings, as pressure/head variations are more easily transmitted through the open voids.

Figure 2-24 shows a general plain view of hydraulic heads for the reference model (R = 110 mm·year-1, K_{massif} = $1 \cdot 10^{-7}$ $m \cdot s^{-1}$ and $K_{altered}$ = $1 \cdot 10^{-5}$ $m \cdot s^{-1}$) at elevation -50 m.a.s.l., above 3rd floor of Mosquitera and Pumarabule Mines.

Flow directions in the mine voids are shown with red arrows heading to Mosquitera shaft where the main pumping facility is located. The influence of the mine is shown in the depression of hydraulic heads near the workings, as pressure/head variations are more easily transmitted through the open voids.

The hydraulic heads in the interior of the conduits change with a very low gradient and between the shaft and the farthest galleries the differences are, in general, of less than 1 m. The mine voids cause a drain effect in the massif and affect a large altered volume.

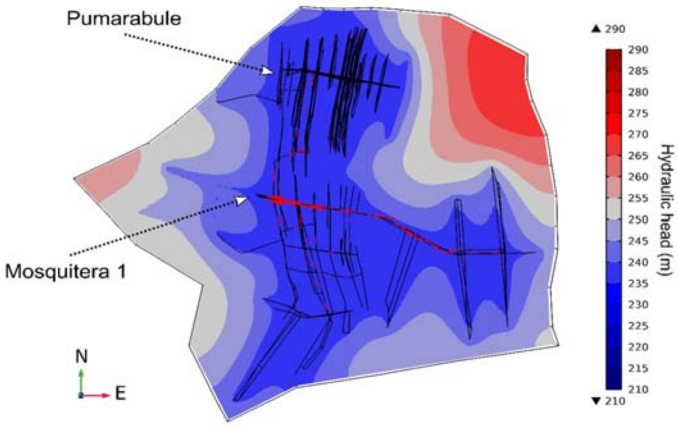


Figure 2-24: Example results of hydraulic head distribution at -50 m.a.s.l.

Parametric sweep and Monte Carlo simulations were run to explore the impact of variations in the main parameters of the model. These variations include: permeability in the altered and unaltered massif, recharge values, conduit section variations (such as caused by convergence o collapse of the mine voids), permeability and thickness of exploitation zones (panels) and river conductance.

To evaluate flow rates and main flow-paths, as well as identify zones where regime might be turbulent, several models changing hydraulic parameters and recharge values were run. Reynolds' numbers were utilized to indicate critical zones in which flow would be turbulent and provide orientation about the limits of applicability of laminar flow laws. Re>4000 indicates turbulent flow, while Re<2000 is characteristic of laminar flow (Figure 2-25).

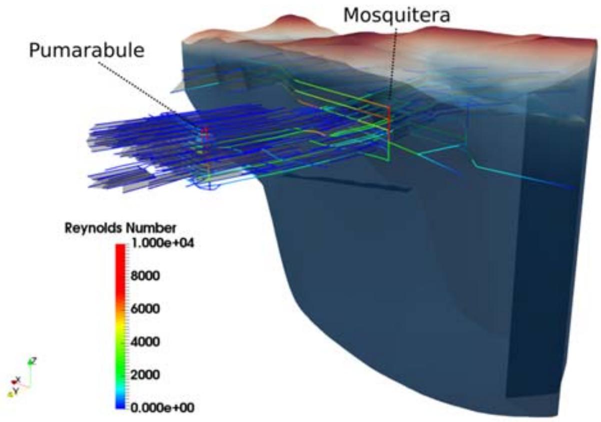


Figure 2-25: 3D view of the model showing Reynolds' number in the mine conduits. Turbulent flow regime in the shafts, main roadways near the shaft and mine communications

A classification of ranges of calculated velocities in the mine voids was done. These values agree with results from tracer tests in the literature and show the very high variability of velocities in the mine.

Groundwater models include Candín River to analyse and evaluate the possibility of water loss (from the river to the mine) or discharge (from the mine to the river). A potential zone of river loss has been identified on a stretch where the river flows above the mine workings.

The potential infiltration would be related with subsidence and alteration of the massif caused by the mine workings, and would require further investigation, including differential gauging in the river.

The capacity of pumping facilities to remove the necessary volumes has been proven satisfactory until now. However, it has been recognized and evaluated the potential risk of water discharges to the surface that would have negative environmental impacts because of the presence of associated chemical species.

A potential area of discharge has been identified after modelling in the Valley of Candín River, southbound of Tuilla and Mosquitera 2.

It has been also evaluated the extension of the potential surface discharge area. Figure 2-26 shows the areal extension of flooding zone obtained in the most negative (in terms of risk) models ran. These results were obtained with extremely high rain and very low hydraulic conductivity in the massif and conductance in the river.

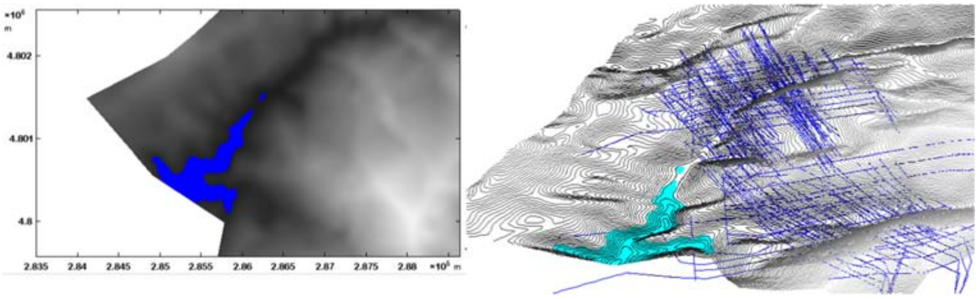


Figure 2-26: Maximum calculated flooding potential zone fro Spain

Results of inundation risks should be analyzed in terms of groundwater flooding, which occurs when the water table in permeable rocks rises above the ground surface. The very low permeability of the carboniferous unaltered massif reduces the possibility of groundwater flooding, but groundwater levels at Mosquitera piezometers should be monitored to prevent further impacts.

Besides, actual water level (235 m.a.s.l.) is above the shallower mine floor of Mosquitera (229 m.a.s.l.). It also should be evaluated a potential risk accounting for a sudden rise of water level and/or pump malfunction in the shafts, that would be critical, as no buffer volume such as an intermediate unflooded floor would be available to impede fast discharge to the surface.

Seven points have been selected within the project that have been considered representative and would be utilized to identify impacts on nearby aquifers. Those with mine influence should be monitored including preliminary hydrochemical analysis. Elevations of the majority of points would prevent polluted discharges from Mosquitera and Pumarabule Mines except in one point, where should be conducted a complete hydrochemical analysis to evaluate possible presence of mine water pollution.

A further result according to the objectives of the study has been the implementation of a contaminant transport model to assess the environmental risks related to the closure of the mine. As open voids constitute the preferential pathways for transported species, groundwater velocities and flow regime in the mine voids have been evaluated to estimate the possible residence times of contaminant species in the galleries.

Contaminant transport models were run using the very limited information available from the mine, including sulphur content of coal seams under exploitation, location of panels and working areas and hydrochemistry data from before and after closure.

Contaminant source concentrations were located in the extraction panels, with a distribution that accounts for the uncertainty and the scarcity of data.

Simulated results show an acceptable agreement with measured data. Maximum contamination occurs approximately one year after the mine is flooded. Results also show a trend of reduction in contamination that agrees with other case studies in the literature. Iron concentration would be below low pollution limit less approximately 3-4 years after water rebound has been completed (Figure 2-27).

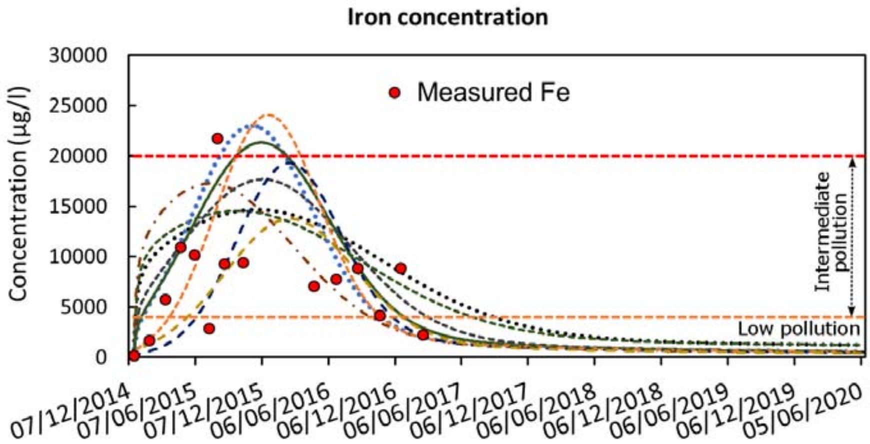


Figure 2-27. Evolution of iron concentration after water rebound

Figure 2-28 shows variation in Fe concentration in the mine voids after 1, 2, 3 and 4 years after the end of the mine flooding. Higher levels of contamination after four years are only in galleries where water velocities are very low, so the flushing of the polluted water is slower.

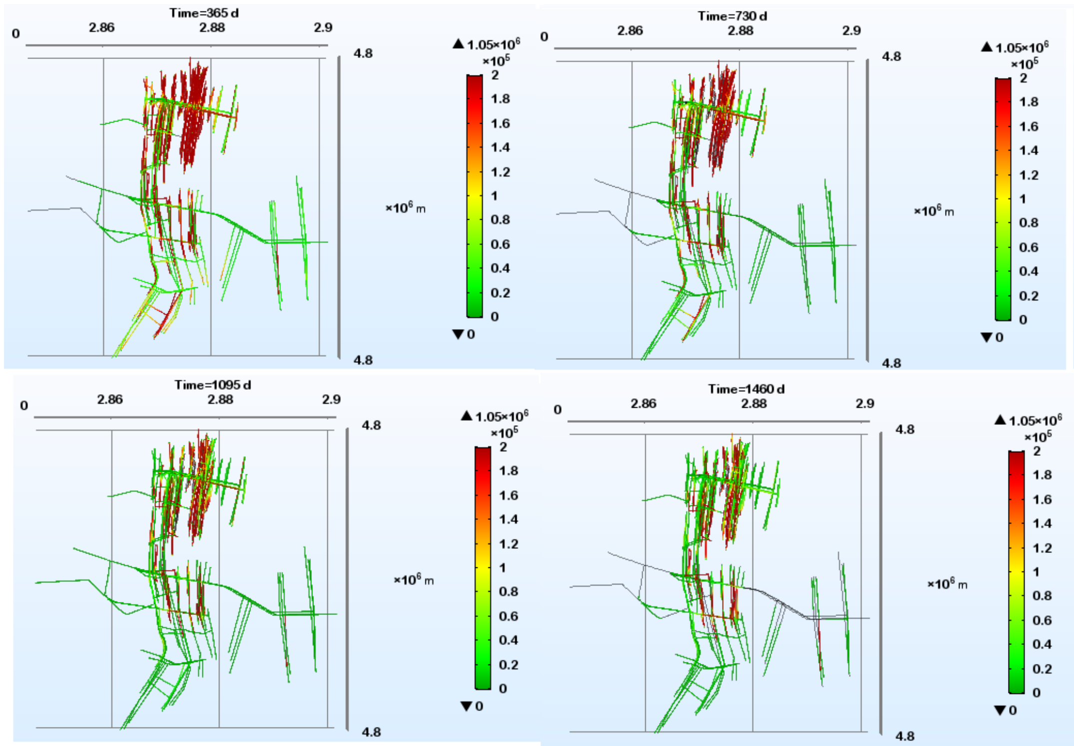


Figure 2-28: Concentration of iron content (µg/L) in the mine voids 1 (upper left), 2 (upper right), 3 (bottom left), and 4 years (bottom right) after the flooding has finalized

T2.3 Development and validation of detailed models to assess the surface liquid emissions and surface water pollution impacts and demonstrate their implementation at the selected PGG and HUNOSA mines (IMPERIAL**, UNIOVI, PGG, HUNOSA**)

The aim of this task was to establish the spatial and temporal variability of the surface water quality parameters for both mines, Mosquitera and Pumarabule Mines (Spain) and Rydułtowy-Anna Mining Complex (Poland) through the use of equilibrium chemical speciation modelling.

The physic-chemical forms in which the studied metals were present were analysed to identify the bioavailable metal concentration. This was also assessed through the use of user-friendly bioavailability tools for both mines, spatially and temporally.

The Windermere Humic Aqueous Model (WHAM7) was used to model the discharged water quality (or surface water quality) at/around Mosquitera and Pumarabule Mines and Rydułtowy-Anna Mining Complex in Spain and Poland respectively.

WHAM7 is an equilibrium chemical speciation model that simulates the chemical reactions that occur when metals enter the water systems. These chemical reactions are critical for understanding how different physic-chemical parameters are affecting the environment.

The model is especially suitable for problems where the chemical speciation is dominated by organic matter (humic substances), where it investigates how metals bind to humic substances, the most dominant form of non-living organic matter in aquatic environments. It is distinctive in including sub-models for the ion-binding chemistry of humic substances (an important constituent of natural organic matter in waters) and natural particulate matter (such as mineral oxides).

Dissolved metals are attached to negatively charged surfaces with large capacity for sorption or co-precipitation with trace metals.

These complexes that a metal can form with inorganic (SO42-, Cl-, OH-) and organic ligands influences the metal speciation, while reducing the free metal ion activity and, therefore, its bioavailability and toxicity, which is important for conducting the environmental risk assessment of metals.

Some elements occur in solution more often in complexes rather than as free hydrated ions.

The WHAM7 geochemical model was used to model the water quality, spatially and temporally. The concentrations of the free metal ions, which are assumed to comprise the 'bioavailable/toxic fraction', as well the distribution of metal species, with respect to inorganic and organic metal complexes, present in the water samples were analysed and quantified.

In addition to the chemical concentrations in the input data file, additional assumptions were also made to run the model:

- As Dissolved Organic Carbon (DOC) is the most common parameter analysed in the laboratory, this needs to be converted to a reactive dissolved organic matter (DOM) fraction. The total DOM has been estimated to be two-times the DOC measured levels and that 65% of DOM behaves as an isolated active fraction. This 'reactive' DOM fraction is dominated by humic substances (HS), comprising, according to solubility, of humic and fulvic acids. Since fulvic compounds generally represent the largest DOM fraction in freshwaters compared to the humic acid, with complexation being stronger with the fulvic than the humic acid, the chemically active DOM fraction was represented 100% by fulvic acid. The remaining 35% was assumed to be inert, with no binding affinity for metals.
- Conventional equilibrium formulations and default constants for the metals binding parameters from the built-in database of the model were used to simulate the reactions.
- Fe, Al and Mn have the tendency to oxidise, hydrolyse and/or precipitate in mine water environments. As pH levels for both mines were not low enough to prevent hydroxides from forming, all the iron and aluminium concentrations were assumed to precipitate as ferric and aluminium hydroxide, respectively; and manganese oxide (MnOx) was considered to be the likely form for manganese.
- The precipitated iron hydroxide was also allowed to have a chemically active surface so as to allow the precipitate to bind ions; an in-built conversion factor related the molar concentration of the precipitated metal to the mass of the iron active phase, to simulate the surface chemistry of 90 g mol-1 iron oxide.

The output matrix of the model provides the component complex concentrations in the aqueous phase, the free ion activity and the fraction of each component for each of the colloidal phases.

The results of the geochemical model provide the spatial/temporal species distribution for copper, zinc and lead. Selected examples for model results obtained for two abandoned coal mine sites are presented here. The water sampling locations at Mosquitera mine (Spain) and Anna mine (Poland) are shown in Figure 2-29.

(a) (b)

Figure 2-29. The water sampling locations at a) Mosquitera mine (Spain), and b) Anna mine (Poland)

Six sampling campaigns were carried out during April, June, August, October, December 2016 and February 2017 covering upstream, downstream and effluent discharge locations around Mosquitera mine. Copper speciation for all the discharge water locations of the Mosquitera and Pumarabule Mines region were dominated by complexation with organic ligands and, therefore, DOC is much more important for determining copper speciation than any of the inorganic complexes (>75%) at spatial scale. Copper was also shown to bind with several inorganic ligands, notably carbonate and bicarbonate, but at a much weaker binding as compared to the organic matter (Figure 2-30). The free Cu^{2+} ion activity, which is considered to be the bioavailable fraction, was present at minimum concentrations.

Two sampling campaigns took place during summer 2017 and winter 2018 at five different discharge locations around the Anna mine. Similar to the Spanish case, copper complex with the dissolved organic carbon was the predominant species, for all the surface water discharges, followed as well, by bicarbonate ($CuHCO_3^+$) and carbonate ($CuCO_3$) inorganic complexes. The free Cu^{2+} ion was also present in a very small fraction.

WHAM modelling predicted that the zinc bicarbonate complex, $ZnHCO_3^+$, was the most predominant species, followed by the free ion Zn^{2+} and the Zn complex bound to organic matter (Zn-FA) for all the discharge surface water locations (upstream, downstream and effluent) around Mosquitera and Pumarabule Mines. However, at lower alkalinity levels, the free Zn ion was the most predominant.

Similarly, the inorganic zinc speciation, for all the discharge water locations at Anna-Rydultowy mine complex, was most important for both campaigns (summer-June 2017 and winter-December 2018). In particular, the bicarbonate complex, $ZnHCO_3^+$ and the free Zn^{2+} ion were the most predominant species, followed by the carbonate, $ZnCO_3$ and the sulphate, $ZnSO_4$ complexes.

The organic Zn (Zn-FA) complex showed lower levels during the summer campaign compared to the winter. That could be indicative of higher dissolved organic carbon concentrations during winter when rainy periods can mobilise the organic matter (Figure 2-31).

The geochemical modelling results for lead at Rydułtowy-Anna Mining Complex region discharge waters showed that inorganic speciation was the most important; with carbonate Pb complex ($PbCO_3$) being the dominant species for the majority of the surface water samples. The organic fulvic complexes were important during the winter period for the industrial sewage discharge at Nacyna stream samples (PS5 and PS6), followed by iron (III) and manganese oxide complexes. The free Pb^{2+} ion was found at very low concentrations.

At Mosquitera and Pumarabule Mines upstream and downstream surface water discharges, the fraction of Pb bound to iron and manganese oxides dominates lead speciation, with Pb inorganic and fulvic complexes predicted to be present at lesser concentrations. The free Pb^{2+} ion activity was very low too.

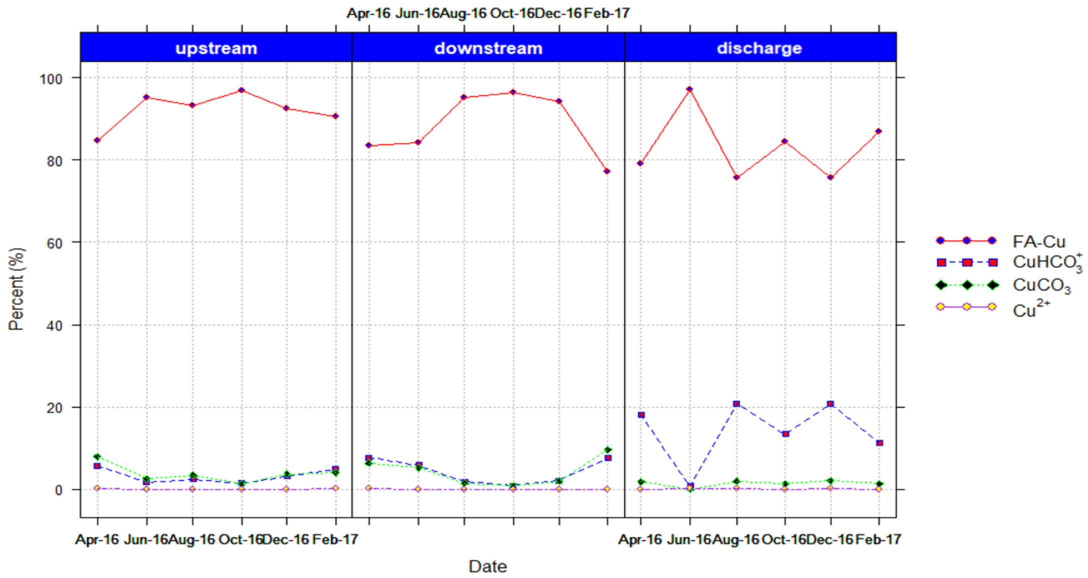


Figure 2-30. Copper speciation in the discharge water locations of the Mosquitera and Pumarabule Mines

These results for each metal speciation distribution agree well with results from speciation studies reported in the literature and show a good agreement within a factor of two between measured free metal ion activities and those predicted using WHAM7 speciation model.

A number of literature studies (including the authors of this document), have demonstrated that organic carbon, manganese and iron influence the speciation of metals, through forming colloidal components/oxides and acting as the major carrier phases that adsorb trace metals, and therefore reduce the predicted free metal ion concentrations. This was shown to be the case for copper and lead for both Spanish and Polish mines studied.

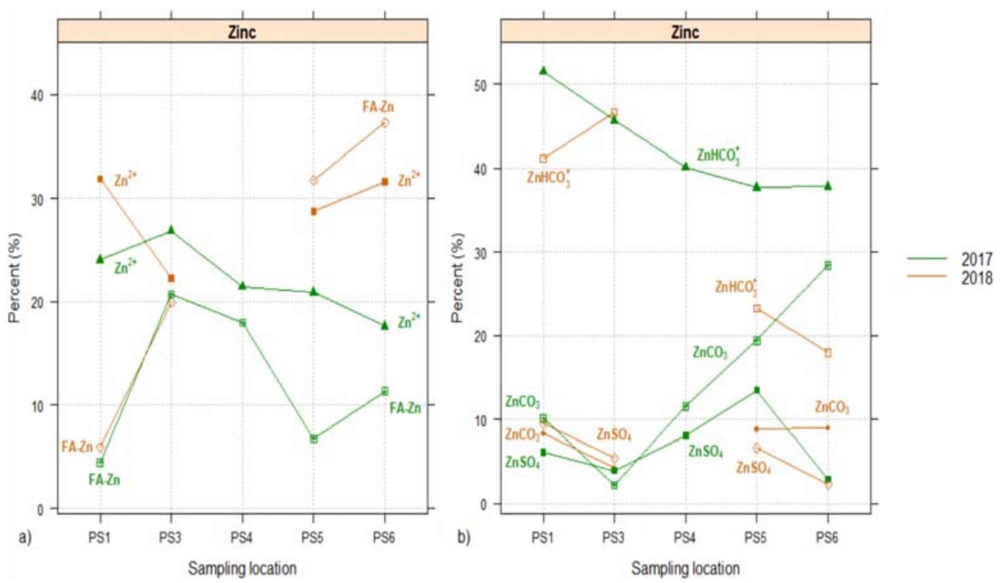


Figure 2-31. Zinc speciation in the discharge water locations of the Rydułtowy-Anna Mining Complex

The geochemical speciation results for the free metal ions provided the necessary inputs for the bioavailability/ toxicity modelling used to perform the environmental risk assessment for surface waters around the abandoned coal mines studied.

T2.4 Development and validation of detailed models to assess the greenhouse gas emissions from closed mines on surface and their implementation at the selected PGG and HUNOSA mines (Ineris, *IMG-PAN, GIG, PGG, HUNOSA* ***)***

The aim of this task was to develop and validate detailed models to assess the greenhouse gas emissions (CH_4, CO_2 and Radon) from the coal mines during the closure and post-closure periods.

As the main assumption, the model includes an analysis of the amount of methane released both during and after decommissioning, and an analysis of possible migration sites to the surface. Therefore, at the beginning it is necessary to determine the value of methane-bearing capacity of the mined seams and average methane emission throughout the life of all longwalls during the mining operation period - for longwalls liquidated within the last 15 years before the date of the beginning of mine closure process (Figure 2-32).

The formula that arise from that model is:

$$\dot{V}_G = 0.2 \times \dot{V}_A (1 - \frac{u}{15})$$

Where $\dot{V}_G$ is the methane emission into a goaf from relaxed overmined and undermined seams during the 15-year period after longwall mining operations cease, calculated for each year separately, in m^3 CH_4/min; $\dot{V}_A$ is the average absolute methane emission throughout the life of a longwall during the mining operation period in m^3 CH_4/min, and u is the number of years after mining operations ceased.

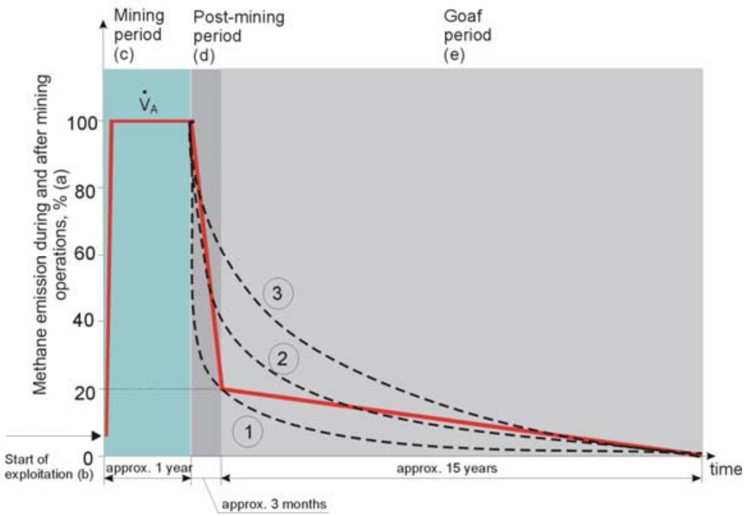


Figure 2-32. Model of methane emission from goafs (Krause & Pokryszka, 2013)

The model assumptions refer to three stages which characterize changes in methane emission into the longwall area during and after mining operations (Krause & Pokryszka, 2013). They are as follows:

1. Mining period: absolute methane emission increases up to the value of the maximum methane emission during the mining period for the given conditions. It usually lasts between a few and several months (approximately 1 year).
2. Post-mining period: this includes the time necessary to prepare and close a longwall (approximately 3 months). Longwall methane emission decreases to approximately 20% of the average value of the maximum methane emission during the mining period.
3. Goaf period: when the absolute methane emission of goafs systematically decreases from the previous value until it reaches almost zero after 15 years.

Each mined longwall in a gassy seam, depending on its orientation towards relaxed gassy seams, will have a unique course of methane emission during and after mining operations.

The model of methane emission from undermined and overmined seams into goafs after mining operations depends on the value of the mean absolute methane-bearing capacity of the production period (Krause & Łukowicz, 2000).

The model assumes that after closing the shafts, the mine voids are treated as a reservoir in which the methane concentration will change because of methane emission from goafs (Figure 2-33), where:

- Q_P: the total incoming flow of gas.
- Q_A: the incoming flow of atmospheric air.
- Q_D: the incoming flow of firedamp desorption (m^3/day).
- α: the firedamp desorption flow-rate depending on the reservoir pressure (m^3/day.Pa).
- ß: the firedamp desorption flow-rate independent of the reservoir pressure (m^3/day).
- ɣ the atmospheric air inflow flow-rate of the reservoir depending on the reservoir pressure (m^3/day.Pa).
- ΔP: the pressure difference between reservoir and surface atmosphere.

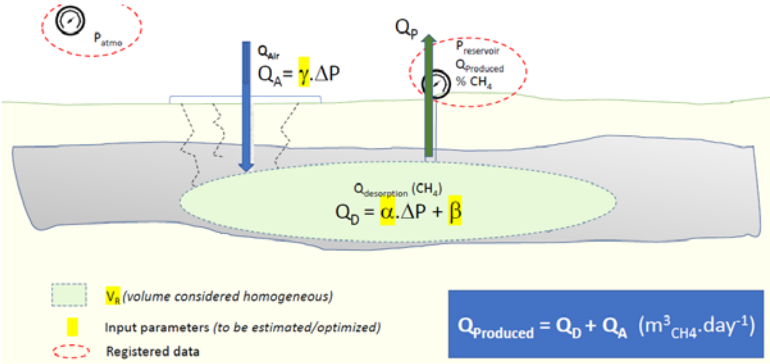


Figure 2-33. Conceptual scheme of the Ineris mathematical model of firedamp reservoir

However, practical application of the model is only valid for specific conditions (Pokryszka and Velly, 2001): (a) the studied reservoir must be isolated from nearby active and ventilated mining workings, (b) the reservoir must be connected to drainage surface installations (the reservoir pressure, quantity of drained gas and its methane content must be registered), and (c) the realistic calibration of the model can be made only with the data obtained during a long period of the gas extraction from studied reservoir.

Considering the fact that the concentration of methane will not be the same in all places of the mine, it is necessary to determine the places of its accumulation. Areas of possible gas migration to the surface are independently analyzed using available information on shallow exploitation, faults, outcrops, and liquidated shafts.

In the final version the presentation of models has been extended with descriptions regarding the steady flow in ventilation systems and post-exploitation voids (goaf) and the specific quasi-static way of modelling gas migration transients, occurring during the liquidation process. Both point and distributed gas emission sources of a time variable characteristics have been considered (Figure 2-34).

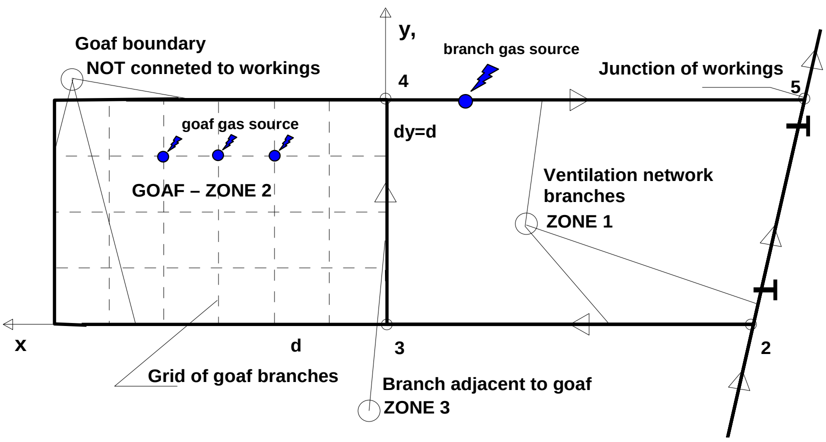


Figure 2-34: Connecting mine ventilation networks with the grid of goaf branches

Then, calibrated models for pre-closure conditions have been developed.

The air densities in branches have been evaluated according to the depth and expected heat release from the surrounding strata. The aerodynamic resistances have been initially calculated upon the geometry and expected wall roughness of the workings.

Then some values have been adjusted, taking into account presence of regulating or separation door, correctness of flow directions and comparison of calculated and measured flow rates.

The process of adjusting resistances resulted in satisfactory accordance of measured and calculated values of flow rates (Figure 2-35).

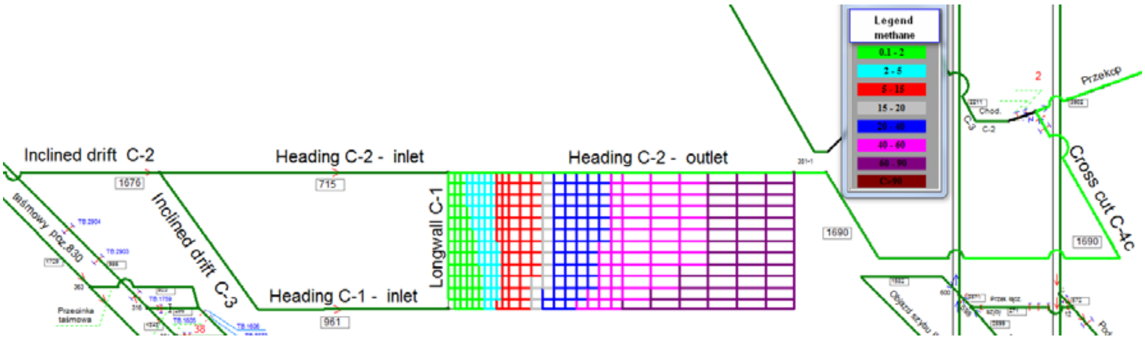


Figure 2-35: An example of methane distribution calculation in a system of connected goaf and mine ventilation network

The physical laws that govern gas flow in the mine voids depend mainly on the processes of gravitational gas transport and pressure differential due to changes in atmospheric pressure and changes caused by the operating ventilation network of an active mine if it borders on a closed mine.

For this purpose it is recommended to use a special software to model gas flow in the mine, i.e. Ventgraph sofware, being necessary to calculate the emission of metate from goafs to the voids of a closed mine.

ANNA MINE (POLAND)

The forecasted volume of methane emitted into goafs in consecutive years is presented in Figure 2-36 and it refers to the goafs of closed longwalls which are not flooded. In addition, elements such as the degree of reconsolidation and the volume of mining galleries must be analyzed. AutoCAD software was used to perform these works.

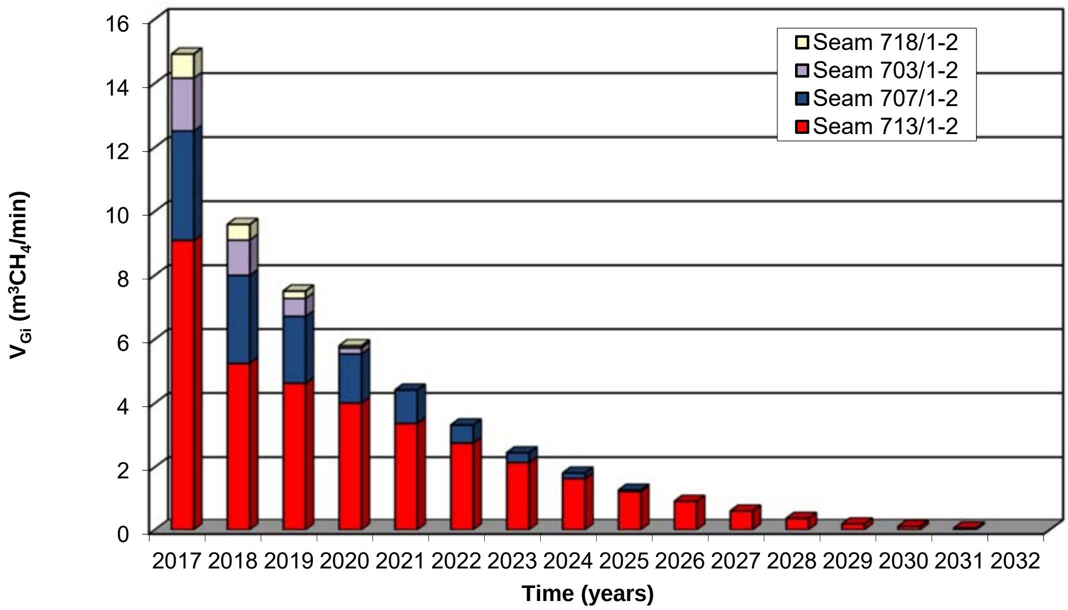


Figure 2-36. Forecasted methane emission into goafs of Anna coal mine seams, 2017-2032

Also, using this software, maps of mine areas and ArcMap and ArcScene software, the percentage of flooding for individual seams of a closed mine was determined. Basing on the developed model of methane emission into goafs in conditions of their flooding, the volume of methane emitted into goafs was verified.

The factor having an impact on the emission of methane released from flooded goafs is the index of methane emission into goafs of distressed seams within the distressed zone depending on the pressure of the water column.

The results of the models allow to gain knowledge about the evolution of the gas hazard in the liquidated mine in the period from the start of closure process to the end of methane emissions from the goafs and stabilization of the risk level.

First of all, the places of methane emission from goafs and the percentage of flooding these places with water were identified (Figure 2-37).

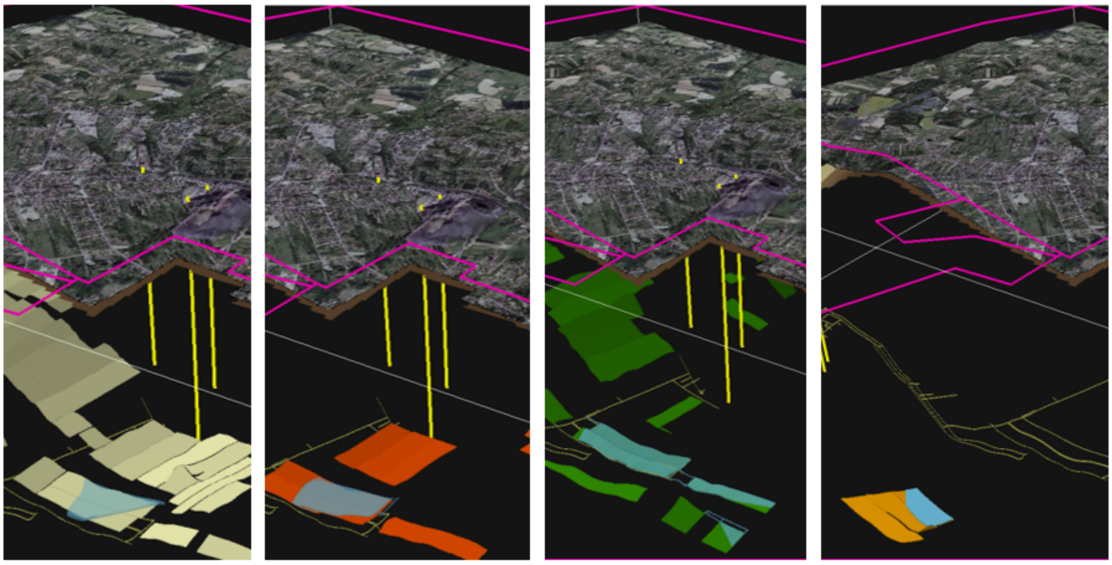


Figure 2-37. Identified places of methane emission from goafs and percentage of flooding

Secondly, comparing the calculated volume of gas evolved with the volume of voids allows for the assessment of the potential gas hazard.

Finally, methane concentrations for individual periods of time in the mine voids treated as a reservoir are calculated.

The use of the Ventgraph program enabled the identification of methane flow paths in a closed mine and the determination of methane concentrations in individual areas of the mine. The results were obtained for the ongoing closure process of the mine (year 2017).

It was assumed that the methane emitted from the liquidated longwalls migrated towards the eastern part of the mine ventilated by the Ryszard II shaft (Figure 2-38).

To illustrate the changes of the ventilation and migration of gases to the Atmosphere during the abandonment, virtual sensors of methane concentration and flow rate were set up at the following locations (Figure 2-39).

Results of gas hazard in a closed mine should be analyzed in terms of places of possible gas outflow to the surface. As the outcome of such case studies, the recommendations on the extent and sequence of sealing off and flooding galleries, shafts and goaf regions may be given.

The final result of the model is a map of the area with identified areas where a risk of gas outflow possibly exists (Figure 2-40).

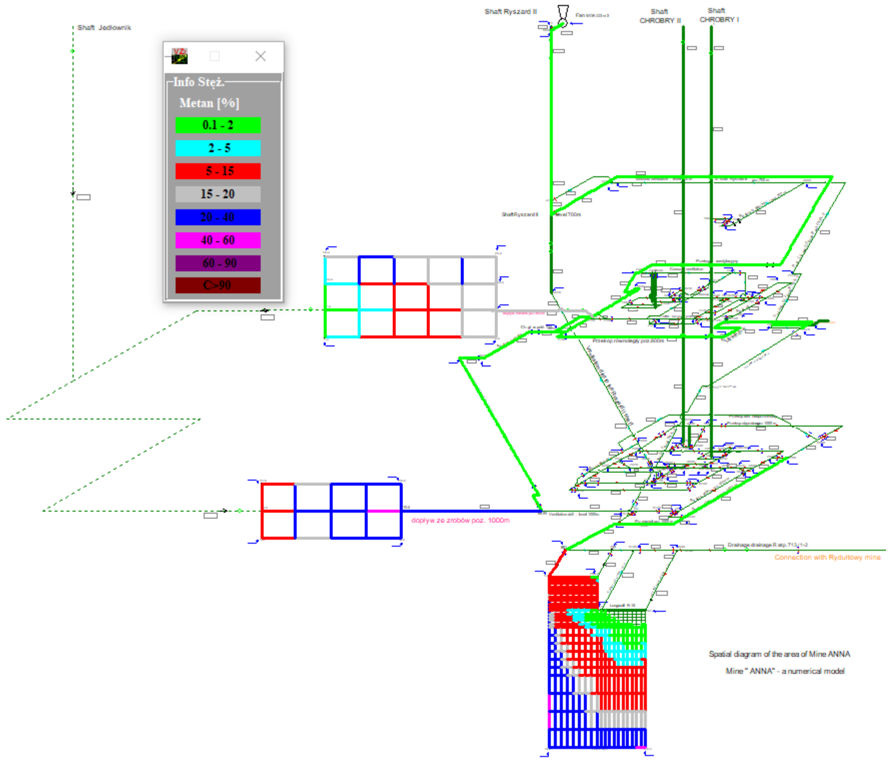


Figure 2-38. Distribution of methane concentration in the ventilation network and goaf for the initial state of the abandonment- fan at the shaft Ryszard II is operating (July 2017)

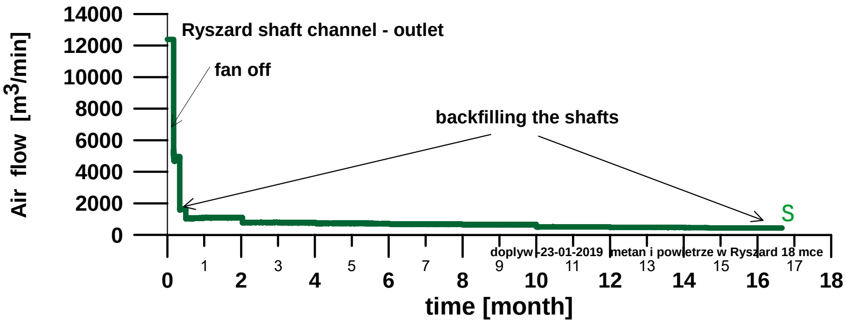


Figure 2-39. Changes of the inflow of the air-methane mixture from the Ryszard shaft to the atmosphere during the abandonment of the ventilation system of the Anna mine

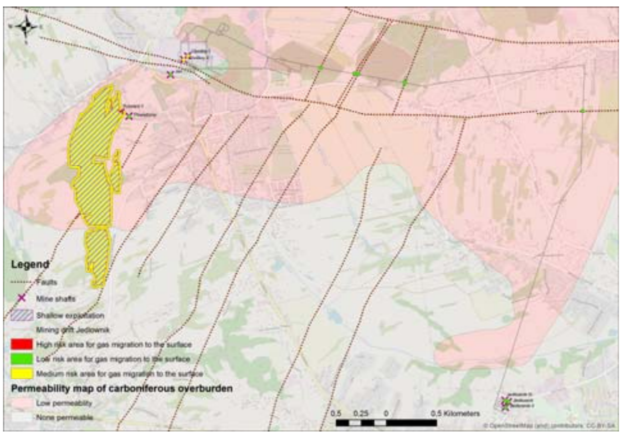


Figure 2-40. Areas of Anna mine area with a risk of gas outflow

SANTIAGO AND SAN ANTONIO MINES (SPAIN)

As Mosquitera and Pumarabule mines were already completely flooded when the project started, that is why it was decided to change the surface GHG emissions modelling to Santiago and San Antonio Mines, as San Antonio was closed and Santiago was still working. Thus, it was possible to assess the gas emission risk for this area in conditions previous to the flooding.

As Santiago is connected with San Antonio (1947-2003) within the same ventilation network, the gas risk was assessed for the two mines together. The assessment did not consider an increase in gas hazard resulting from flooding as the mines for the moment will not be flooded.

The volume of emitted methane is a parameter which can be assessed following the model of methane emission from panel goafs after finishing mining operations in Santiago mine.

Relating Santiago mine, as in Spain coal seams are subvertical, the exploitation of a coal seam is divided into panels and each panel is exploited for around 2-3 years. Then the exploitation continues with an upper or a lower panel, but within the same coal seam.

Ventilation goes around the panels of the same area till the exploitation finishes. That is why, instead of analyzing the emission of gas of each panel separately, emissions of different areas (sets of panels) were analyzed.

For this purpose, the model was modified considering the fact that in Spanish mines occur highly inclined seams (subvertical seams). Instead of a coefficient of 0.2, for mines were coal is deposited in steep seems, increased methane emission was considered and the coefficient used was 0.3:

$$\dot{V}_G = 0.3 \times \dot{V}_\mathrm{A} (1 - \frac{u}{15})$$

To assess the risk associated with methane emission, the amount of the gas emitted from the goafs (throughout 15 years after the mining operations in the last panel stopped) was analyzed.

The total volume of methane emitted from goafs between 2019 (after closing the panels) and 2033 (the end of methane emission) was forecasted at the level of 1,522,195 m^3.

RADON

One of the hazards found in underground mines is caused by ionizing radiation. The source of this radiation is radon and its short-lived decay products. Radon which is exhaled from the rocks surrounding the headings undergoes radioactive decay, and this is carried together with the decay products through the mine headings by the flowing air.

Isotope atoms bond with liquid and solid particles suspended in the air inside the mine whilst they are being carried by the air and form radioactive aerosols. Aerosols inhaled with the air and deposited in the human respiratory system cause irradiation of its tissues, causing various forms of cancer. Consequently, it is of great importance to learn the distribution of the concentration of radon and its decay products in the headings which form the ventilation system of a mine.

The diverse radon sources, such as the rocks at the roof, the floor and side walls of corridor headings, and rock materials filling the caving zone are also taken into account.

It is possible to establish the concentration of potential alpha energy $C\alpha$ and the Exposition E or Working Level Month (WLM) if the activity of radon and its decay products is known anywhere in the mine. The Exposition is a measure of the radiation dose received in time t, and WLM is the measure of this dose during the time interval of 170 hours.

A useful tool which enables the prediction of the concentration of radon and the products of its decay in the ventilation system of a mine is provided by a computer simulation (Briondal and Moridi 1999).

The simplest and most popular approach for underground mine ventilation systems is based on a one-dimensional flow approximation and a concept of a network, where shafts, galleries and longwalls are termed network branches, and places where they intersect are called nodes. The unknown values for the branches are the flow rates and for the nodes - the pressures. Calculated values are validated against in-situ measurements.

The computer Software Ventgraph, developed since 1988 at the Strata Mechanics Research Institute (Dziurzyński, Pałka and Krawczyk 2013) is based on this approach. In Ventgraph, the basic network flow model has been extended by several features, such as the process of gas propagation.

The distribution of the concentration of a given gas along a branch may be evaluated when gas sources are introduced, and the streams of gases are mixed at junctions. Hence, it is possible to obtain the profile of the concentration of the gas in the network and the properties of the stream reaching the atmosphere at the surface.

Supplementing this software by modules modelling radon exhalation, its radioactive decay and the losses during transport in the ventilation system of a mine provides a tool which may be used to predict the radiation hazard in underground mines.

Figure 2-41 presents the calculated distributions of radon concentration as bold colored lines scaled according to the color scheme shown, based on the distribution of radon concentration and the concentration of potential alpha energy, as calculated with the use of the VentGraph-Plus-module Radon programme.

The calculated distribution for radon concentration considered the losses caused by diffusion and gravitational sedimentation for each heading and in the area of the goaf of longwall R-15 and the goaf of liquidated longwall R15a.

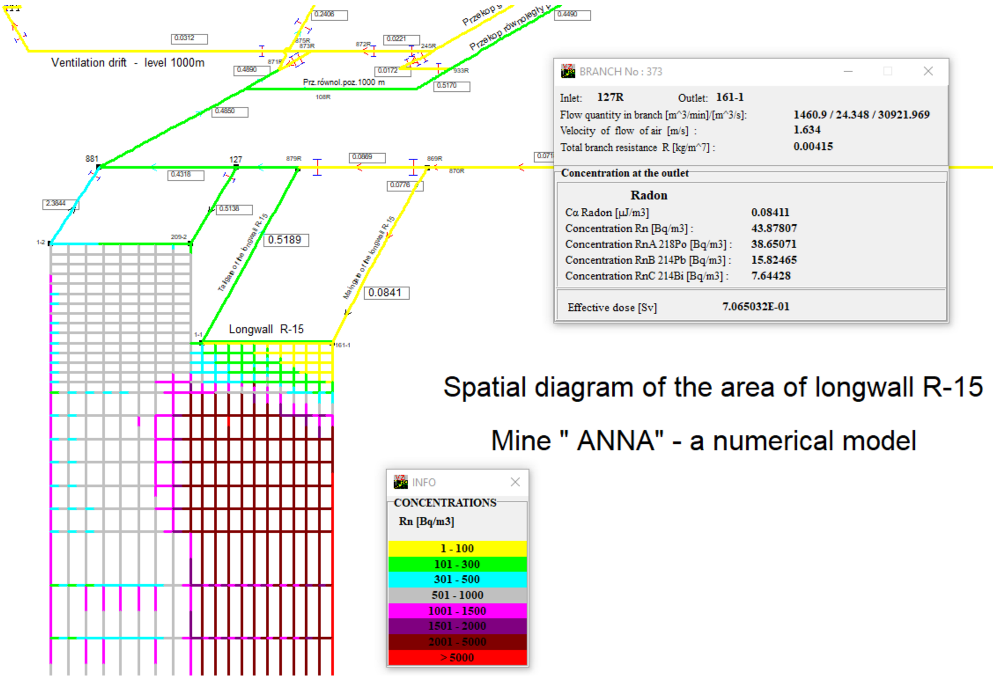


Figure 2-41. Spatial diagram of the area of longwall R-15, rate of flow = 1461 m³/min, distribution of radon concentration in headings and gob

Figure 2-42 presents the calculated distribution of radon concentration in the goaf of longwall R-15 and in the goaf of liquidated longwall R-15a, and high contents of radon are observed in the area of the headings, which is also a function of the amount of air migrating to the goaf.

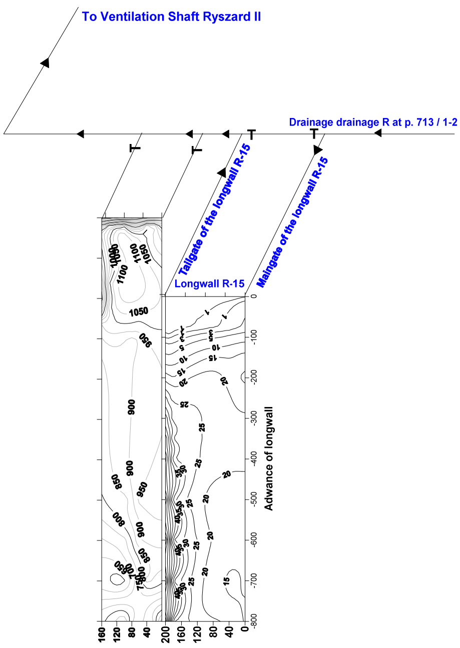


Figure 2-42. Distribution of radon concentration in headings and gob

When calculating the level of radon contamination of mining headings in the area, as well as the goaf and ventilation routes, the choice of values of parameters for the radon exhalation source for each heading, when taking into account the relatively small number of measurement points is critical.

Figure 2-43 presents the locations for the measurements in the headings of the Anna mine carried out by a team of academics of the Central Mining Institute, Katowice.

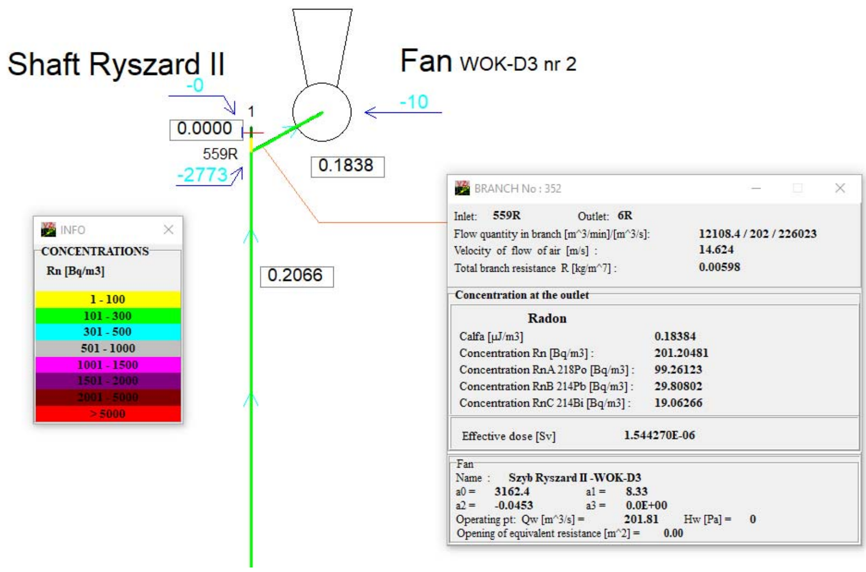


Figure 2-43. Spatial diagram of the Anna mine, fan duct WOK-D3–Ryszard II shaft, air outlet from mine

Concluding, all problems, related to exposure to indoor radon in dwellings and at workplaces, and identification of so called radon prone areas followed by recommendations for the Member States, are specified in the Council Directive 2013/59/EURATOM on 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom (L 13/1, 17.1.2014).

***T2.5 Integration of environmental impact estimates in the ArcGIS database (DMT,** IMPERIAL)*

In this task the modelling results were integrated in the database and the web-based visualisation environment, allowing the joint interrogation and interpretation of the subsidence, groundwater and surface water and gaseous emissions in the Web-GIS integrated modelling system. The GIS database was also populated with available regional data, so the spatial distribution of environmental impacts can be considered in relation to sensitive receptors.

The combination of different data sources, formats and types from continuous and spot monitoring, high and low frequency data, modelling results etc., through a common and integrated database was absolutely necessary in order to support accurate and integrated impact prediction.

The developed GIS database is completely free access to the public in general at:

URL: https://safeguard.dmt.de/merida/?lang=en

When accessing the GIS, the first screen to appear corresponds to Rydułtowy-Anna Mining Complex (Poland) and the shafts of the complex.

If the user wants to select the other case study, Mosquitera and Pumarabule Mines (Spain), it has to access the menu that is situated in the bottom left. In order to start with the GIS the tools menu can be accessed in the upper right part of the screen. Once the tools are activated the "Layer" menu can be accesed.

As an example, in Figure 2-44 are presented the mining drifts corresponding to Jedlownik.

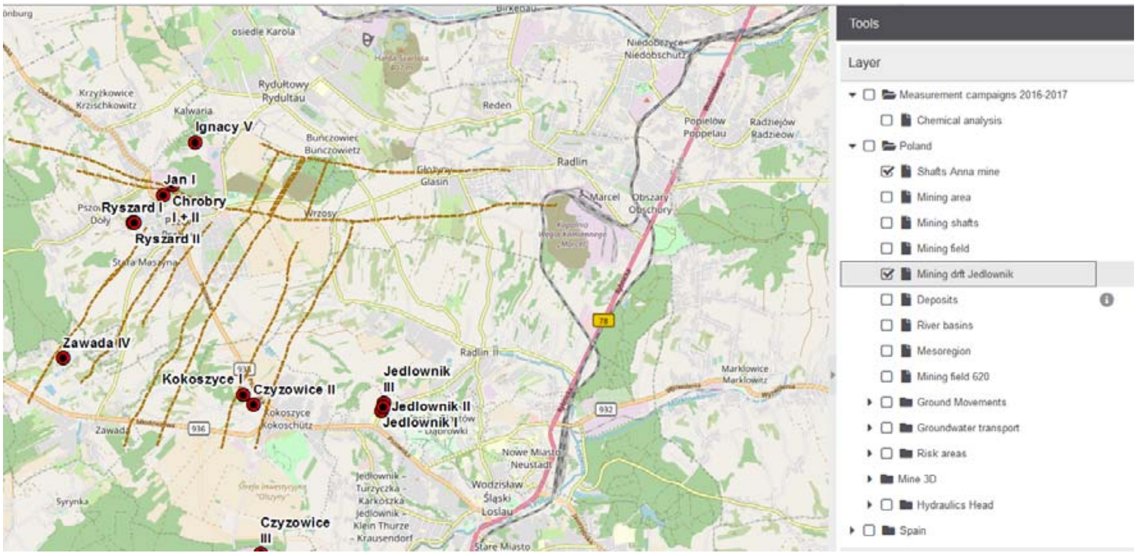


Figure 2-44. Mining drift Jedlownik

Addressing ground movements Figure 2-45 presents them with the mine flooded up to -800m and with 67 longwalls flooded. The maximum uplifts are 39mm.

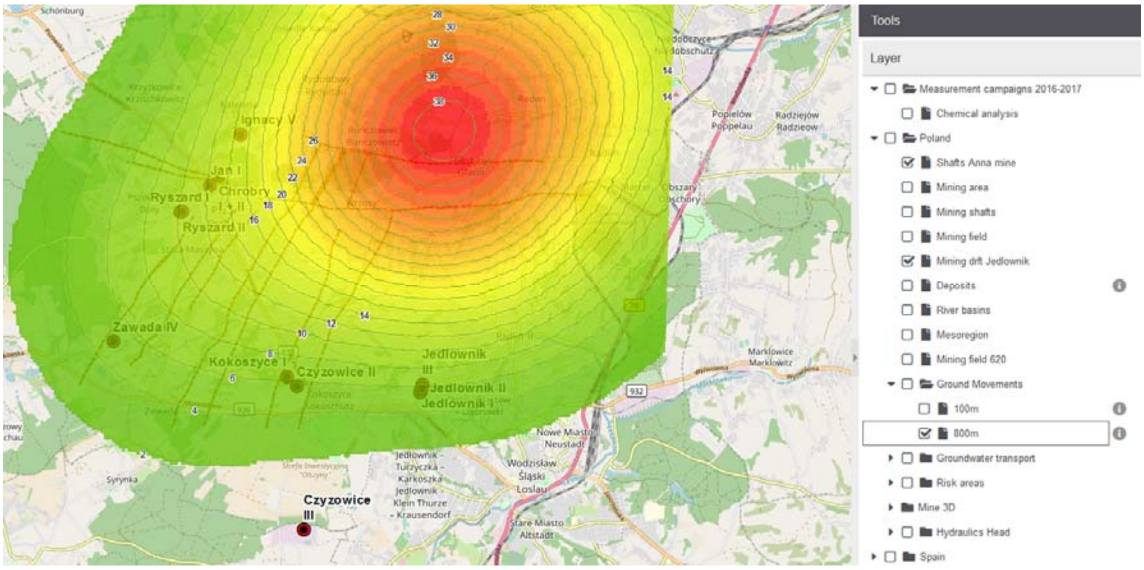


Figure 2-45. Ground movements when flooding up to -800m

Addressing the potential groundwater pollutant transport risk in the surface aquifer, the GIS allows representing the different plumes for sulphates, chlorides, iron, solute and manganese.

Figure 2-46 presents the predicted plume for chlorides for the first year of the forecast.

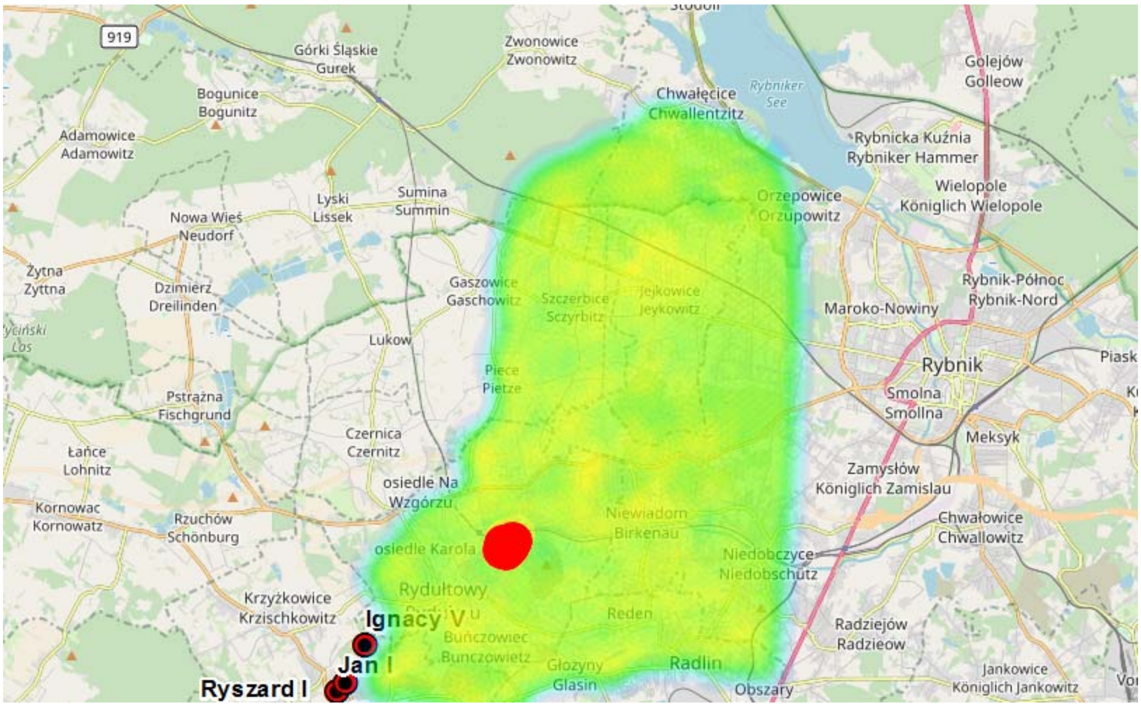


Figure 2-46. Chlorides plume (red) predicted during the first year and superimposed over the footprint of the surface aquifer

Figure 2-47 presents the 3D model of Anna Mine, with an independent menu that allows accessing all the different elements of the model.

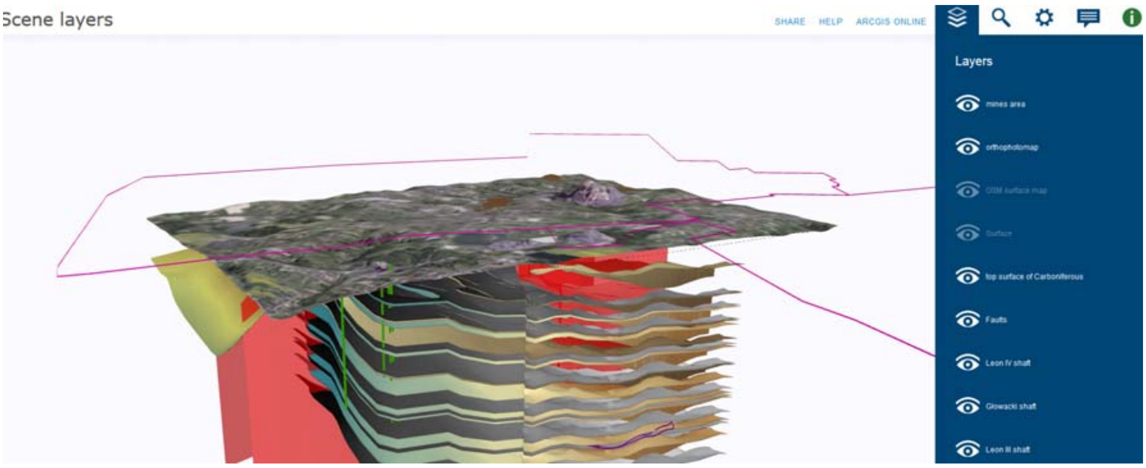


Figure 2-47. 3D representation of Anna Mine model

Addressing surface water quality analysis, Figure 2-48 presents the different locations around the Rydułtowy-Anna mining complex, where surface water discharges were sampled for chemical analyses during the measurement campaigns of 2016-2017.

Clicking in any of the points it is possible to access to the chemical analysis of that point.

By clicking on the configuration button, it is possible to access the Diagram configuration, in order to select the variables that want to be analysed.

Using the configuration button it is possible to access the graphic representation of the selected variables being possible to elaborate a template for the analysis, to select the period to be analysed, etc.

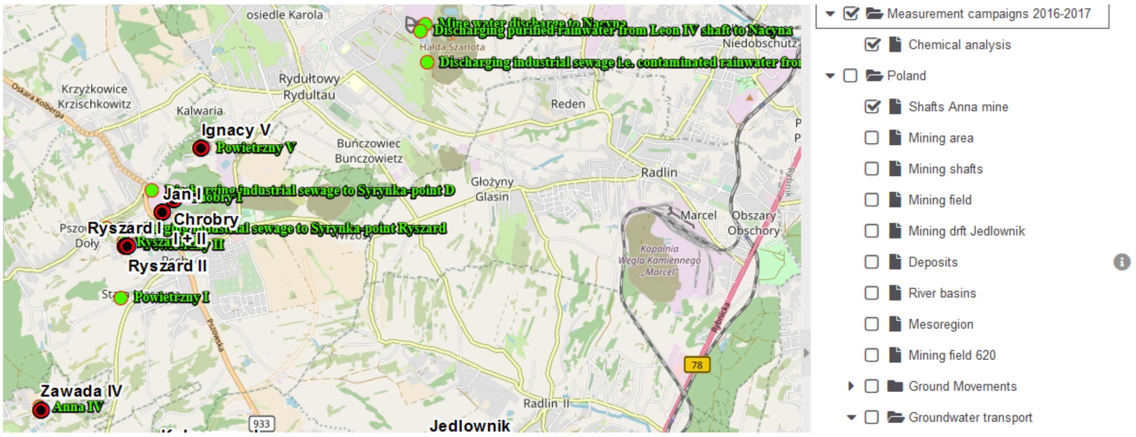


Figure 2-48. Surface water sampling locations of the measurement campaigns around Rydułtowy-Anna mining complex

The GIS is also developed for Mosquitera and Pumarabule Mines in Spain together with an analytics tool that allows to undergo different kind of analysis, even simultaneously regarding different hazards. It has to be highlighted that when zooming into the opaque areas it is possible to see the topographic map below, although in these figures looks completely opaque.

Figure 2-49 presents the flood probability in the area of Mosquitera and Pumarabule Mines.

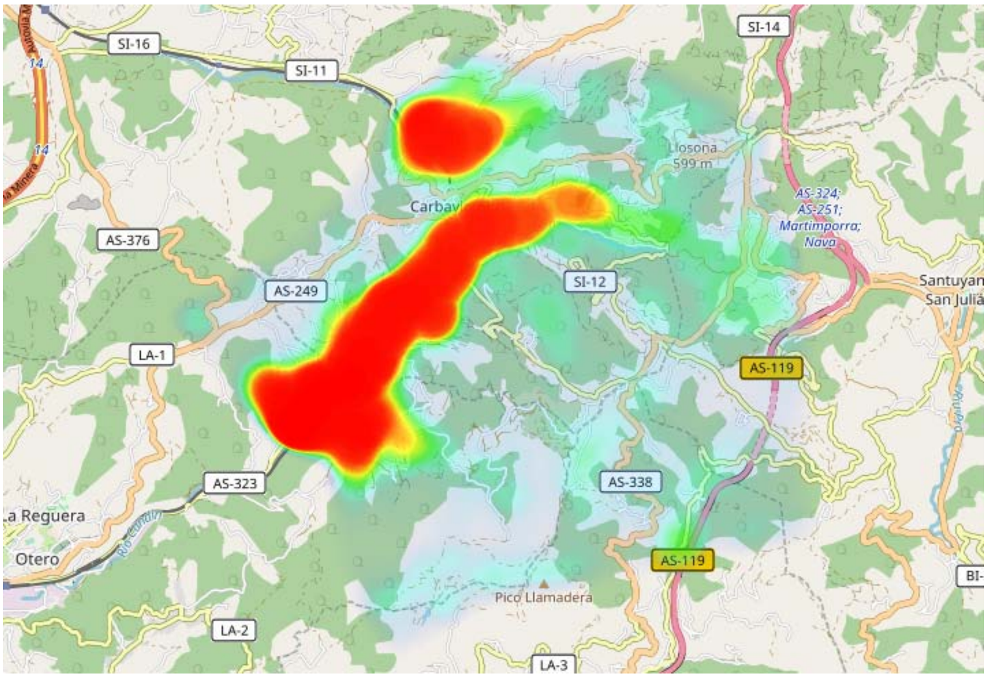


Figure 2-49. Flood probability in Mosquitera and Pumarabule Mines

Figure 2-50 presents a combination of flood probability and ground movement damages.

Figure 2-51 presents a combination of hydrovelocity heat map and flood probability and Figure 2-52 presents a cross-section of flood probability.

As it can be seen, there is a huge combination of possibilities in order to analyse the interactions among any variables.

Figure 2-50. Combination of flood probability and ground movement damages

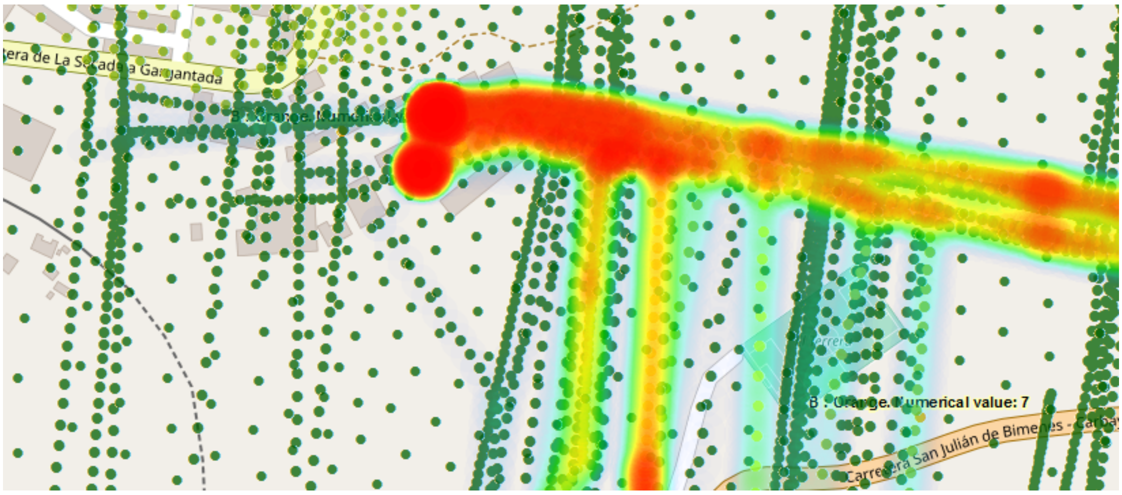


Figure 2-51. Combination of hydrovelocity heat map and flood probability

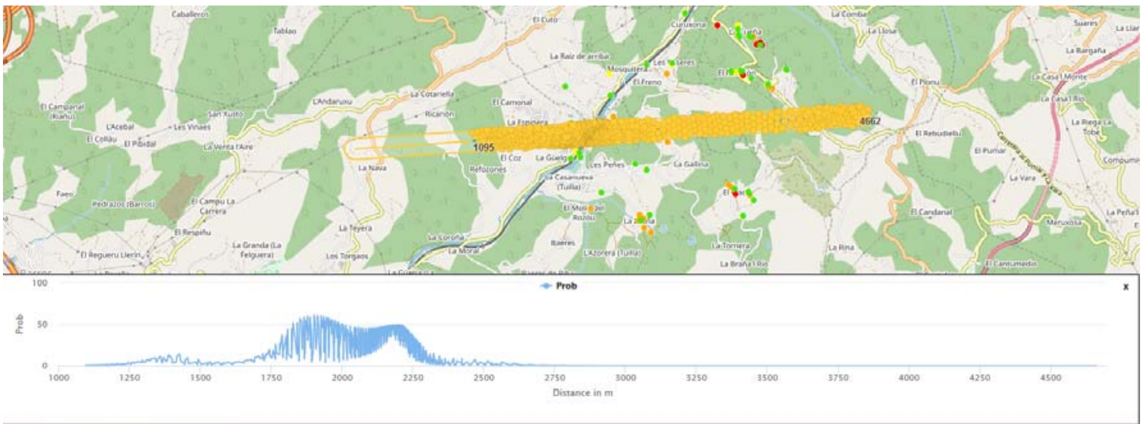


Figure 2-52. Cross-section of flood probability

2.3.3 5.3.3 Work Package3: Risk Evaluation

T3.1 Subsidence (ground movement) risk assessment at the selected PGG and HUNOSA mines (IMG PAN, GIG,** VSB, PGG, HUNOSA**)

The main objective of this task was to assess the risk of continuous and discontinuous deformations because of the liquidation works carried out in the mines. As mentioned in previous studies, the liquidation of underground mining excavations through flooding involves certain geomechanical problems associated with changes in the properties of rock mass and the pressure inside. The arising movements occurring in the rock mass due to these changes can lead to damage of buildings located on the ground surface. This is mainly caused by surface or linear type discontinuous deformations.

ANNA MINE (POLAND)

Risk identification

The liquidation of underground mines by flooding poses some geomechanical problems related to the changes in the properties of rock mass and the pressure inside it. These changes cause a disturbance of the initial state of stress and strain, which often results in the movements of the rock and soil strata.

The flooding of the mine is carried out by ceasing to pump water out of the mine, which leads to the restoration of hydraulic pressure. The natural hydraulic equilibrium in the saturated rock mass is a spontaneous and long-lasting process.

Figure 2-53 presents the main ground movement hazards related with mine flooding.

Figure 2-53. Diagram of the ground movement hazards related with mine flooding

Relating continuous deformation, the movements of the rock mass during mine flooding take the opposite direction to those observed during mining operations. The phenomenon of ground surface heave (uplift) is often observed, which is closely related to the changes of internal pressure in the flooded regions and the force they exert on impermeable overlying strata.

Compared to massive rock formations, the permeability of fractured rocks is much higher, which is why the deformation of strata appears mostly in goaf regions. In the broken rock zones (i.e. areas where rocks caved in and cracked as a result of a mining operation, thus significantly increasing its permeability), one can observe a pressure increase in the formed fractures and pores, which consequently leads to vertical deformation (expansion) of this zone.

The land surface displacements arising from the goaf flooding process are much smaller (measured in centimetres) and manifest very slowly but in a wider range compared to the land deformation created by mining extraction. The danger degree of the hazards related to continuous surface deformation can be defined as small or very small in comparison to discontinuous deformation (Figure 2-54).

Relating discontinuous deformation, international literature describes various cases of rock mass movements in the form of ground surface uplift, which additionally involve damage to civil structures. Such situations are mainly due to discontinuous deformations of surface or linear type. In addition, as a result of the displacement of the uplift and cracking in hard rock strata, it is possible to record dynamic phenomena in the form of tremors.

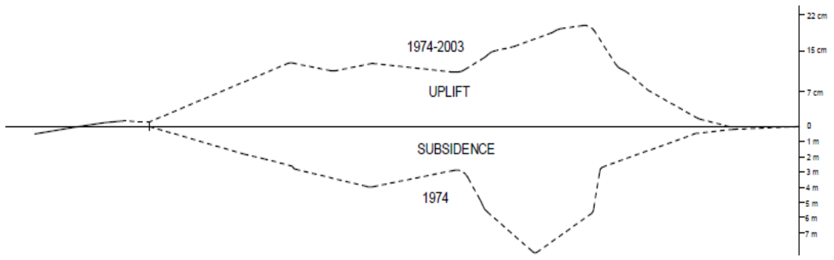


Figure 2-54. Uplift and subsidence of the surface (Pöttgens, 1985)

The discontinuous linear deformations occur mainly in the fault outcrop areas. As a result of these changes in the stress conditions, a slip may occur on fault planes, which then becomes visible on the ground surface (mostly linear type but in some cases also surface type).

Many researchers performed simulations of stress and displacement evolution of faults under the combined action of mining and water pressure. Performed analyses show that during the process of working surface advancement, the stress and displacements in the contact surface of the fault increases.

What is more, in comparison with upper stratum, the movement of the lower stratum is more significant (Zhang et al 2016).

In addition, it is found that the evolutionary nature of water inrush is the erosive process of fault zone material, and is pointed out that the fault damage and its neighbourhood rocks, is the precursor process of water inrush.

All presented threats, under appropriate conditions, can lead to visible surface deformations and as a consequence, damage to objects/civil structures located on the land surface and/or environment. In order, to determine the degree of hazard during the mine liquidation by flooding, risk stages were created and analyzed.

Three stages have been chosen for Anna mine, in which the occurrence possibility of mentioned ground surface hazards have been analyzed: (1) flooding Anna mine to the depth of -801 m.a.s.l., (2) flooding Anna mine to the depth of -801 m.a.s.l. and water overflow to Rydułtowy, and (3) flooding Rydułtowy mine to the depth -720 m.a.s.l. (safe depth of flooding for neighboring mines).

Due to the small difference in the depth of flooding and possible potential effects on the land surface in stages 2 and 3, they are analyzed together in further risk analysis. In the further part of the risk assessment associated with ground surface deformation for Anna mine is presented.

Risk analysis

<u>Stage I - The ground surface uplift during the closure of Anna mine – flooding to depth -801 m.a.s.l.</u>

To assess the risk associated with ground surface continuous deformation, the deformation indicators have to be estimated, ea. uplift (vertical deformation). The analysis considers flooding of the Anna mine to the depth -801 m.a.s.l.

Predicted uplift for Anna mine obtained using Sroka's method (area with uplift marked in blue and flooded regions marked in red) is presented in Figure 2-55.

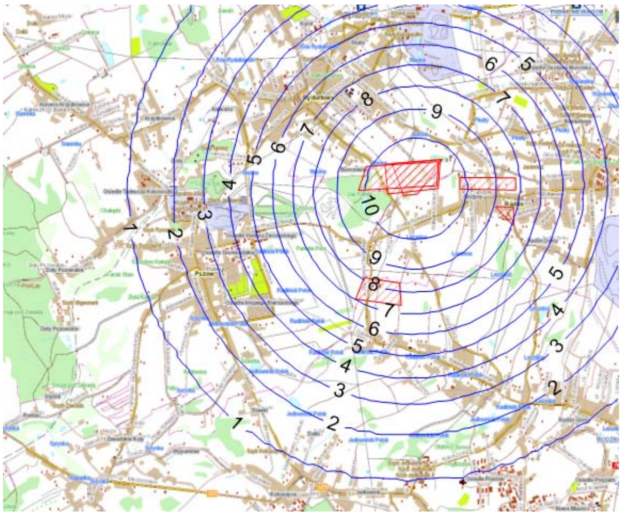


Figure 2-55. Predicted uplift for Anna mine obtained using Sroka's method

The flooding analyses have been performed using two methods and presented in D2.1 project deliverable. In the first method, maximum vertical displacement approx. 11 mm has been obtained. Calculations using numerical method showed a similar value to one from the analytical method, which was approx.10 mm.

<u>Stage II - The ground surface uplift during the closure of Anna mine – flooding to depth -801 m.a.s.l. and water overflow to Rydułtowy mine</u>

The analyses have been performed in similar way as was to be for stage I. Calculations have been carried out using analytical Sroka's method proposed by the authors. In this stage, flooding to depth -801 m.a.s.l. with water overflow to Rydułtowy mine has been considered as a result of breaking the protections' tightness.

In this calculations, the flooding of 71 mine workings was simulated, situated at a depth to -801 m.a.s.l. both in the Anna mine and in the Rydułtowy mine.

Figure 2-56 presents forecasted uplift, which is the result of flooding the workings located in all considered mines (Anna mine field - orange, Rydułtowy mine field - green, Marcel mine field - violet). The maximum uplift achieved from the forecasting calculations was approx. 40 mm. The results obtained in Stage II analysis due to the small difference in flooding depths between Stage II and III, were adopted in the further risk analysis for Stage III.

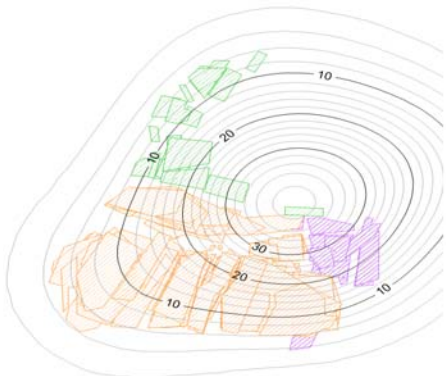


Figure 2-56. Forecasted uplift caused by mine flooding

Risk evaluation for uplift

As it has been mentioned in risk identification part, the first stage of hazard for Anna mine applies only to flooding the mine itself but in the second stage also applies to the Rydułtowy mine flooding by water overflowing from the Anna mine as a result of breaking the protections' tightness. This two stages are treated similar because of low uplift values.

After precise familiarizing with the properties of the rock mass, among others with the existence of natural cracks, voids, layering etc. and using the obtained results of the analyses it was assumed with high probability that flooding the Anna mine region in accordance with the assumptions of PGG mining company will not lead to visible effects on the ground surface.

Authors' experience in the field of rock mass deformations caused by the mine flooding and analyses, which have already been presented in the created reports, let them state that a small risk of damage to buildings on the ground surface and hazards related to environment by continuous deformations. Especially, if cases similar to scenario 1 and 2 are taken into consideration.

The maximum values which have been obtained during the simulations using analytical and numerical methods were close to 11 mm for stage 1 and 40 mm for stage 2 and stage 3 (due to the small difference in the depth of flooding between stage 2 and 3).

Taking into account other deformation indicators, such as e.g. angle of range influence, which is very flat in flooding phenomenon (approx. 10 degrees), and therefore area of heave is very large with low values of uplift and tilt. In such cases that the risk of visible hazards and damages to structures on the ground surface is very low for stage 1 and low for stage 2 and 3, when only continuous deformations are taken into consideration.

The results obtained by applying the proposed methodology of risk assessment are presented in Figure 2-57 for Stage I and in Figure 2-58 for Stages II and III.

Figure 2-57. Risk evaluation for Stage I

Proposed treatments for uplift

To minimise the existing risk, it is necessary to take steps to measure constantly deformation of the ground surface during the mine closure.

Also, all the objects located on the surface requires monitoring, especially long structures, such as pipelines, warehouses, etc.

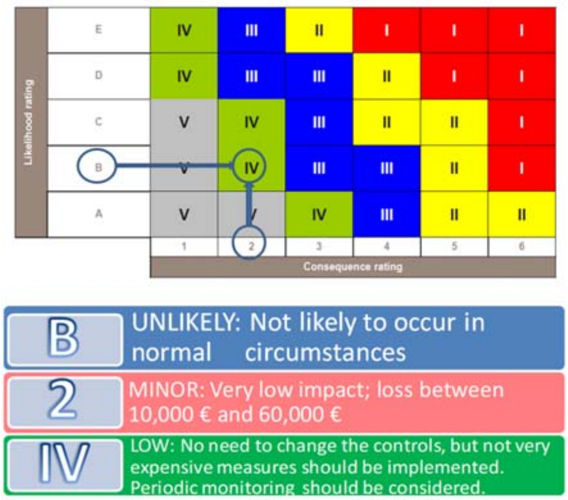


Figure 2-58. Risk evaluation for Stages II and III

In addition, observation of the mine water level and comparison of measurement results with prognostic calculations values should be carried out. If deformations on the ground surface areas with civil structures damages located on it appear, the flooding should be stopped.

Risk evaluation for fractures and cracks

The probability of discontinuous linear type deformations occurrence on the land surface is an extremely difficult task to accomplish. Also, the influence range of this type of deformation is hard to predict due to insufficient data and information on the nature of the fault. The vital importance here is the lack of information on the fault extent in the Carboniferous layer, the location of fault outcrop or possible disappearance in the rock mass.

The authors' experience in the field of rock mass deformations, which have already been presented in the created reports, shows that the possibility of linear discontinuous deformation occurrence on the land surface is possible and may occur under specific conditions and circumstances. If it happens, in authors' opinion, the scale of consequences will be severe and cause serious damages to buildings.

Figure 2-59 illustrates a part of a region disturbed by geotechnical fault (Uskok Rydułtowski II - red dashed line). A zone of potential impact of the fault on objects located on the ground surface has been marked by dashed magenta line.

Figure 2-59. Part of a region disturbed by geotechnical fault. The red color indicates building objects, which may be damaged if the fault will be reactivated

The results obtained by applying the proposed methodology of risk assessment for Stages I, II and III are presented in Figure 2-60.

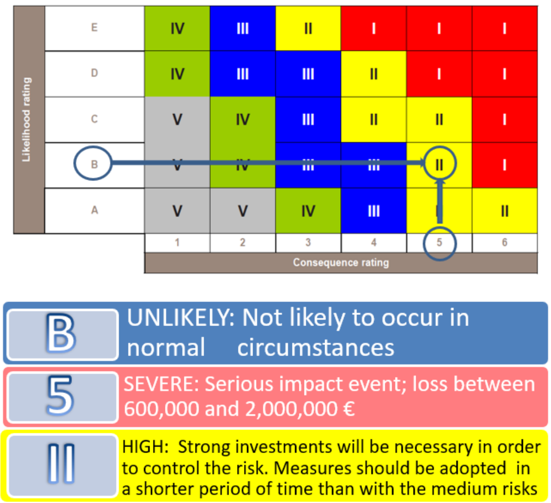


Figure 2-60. Risk evaluation for fractures and cracks for the three Stages

Proposed treatments for fractures and cracks

To minimize the existing risk for buildings currently in the zone of potential impact of linear discontinuous deformation, in the area of the flooded Anna mine, it is necessary to take steps to measure periodicity deformation of the land surface.

Monitoring of the structures should be understood as a measurement of object strains, displacements, tilt (especially long buildings), and regular objects inventory in search of damages (scratches, cracks).

Risk evaluation for sinkholes

The only situation when the sinkhole can appear during flooding operations is the one in which the slippage of the fault appears (Figure 2-61).

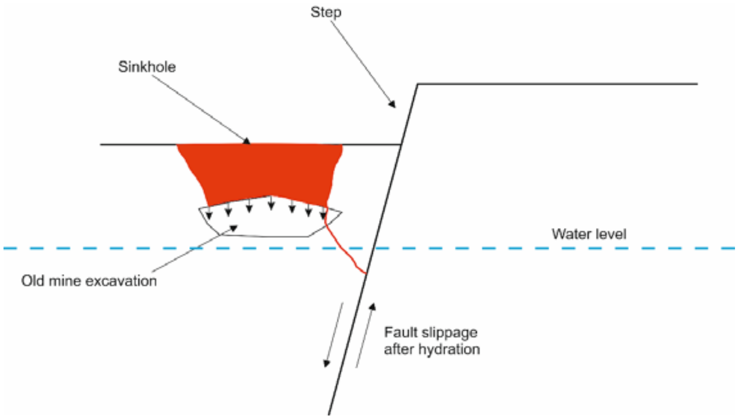


Figure 2-61. Fault slippage after hydration

The formation of such deformation is favoured by the existence of shallow old mining exploitation in a short distance from the fault. Figure 2-62 presents the example region located in the Anna mine area. Old shallow exploitation is marked in magenta by hatched region, nearby faults by magenta dashed line and possible damaged objects are marked in red.

The range and precise determining the location of the possible sinkholes is currently impossible due to the fact that there is a lack of important information (like predicted fault outcrop in quaternary).

Figure 2-62. Area of old shallow exploitations and possible damaged objects in the Anna mine area

Based on stage I and II of the analyses performed for Anna mine, and data obtained from PGG Company, risk occurrence of the surface type discontinuous deformation on the ground surface, as a result of mine flooding to the depth -801 m.a.s.l., should be considered as very low (but possible in specific conditions).

The results obtained by applying the proposed methodology of risk assessment are presented in Figure 2-63.

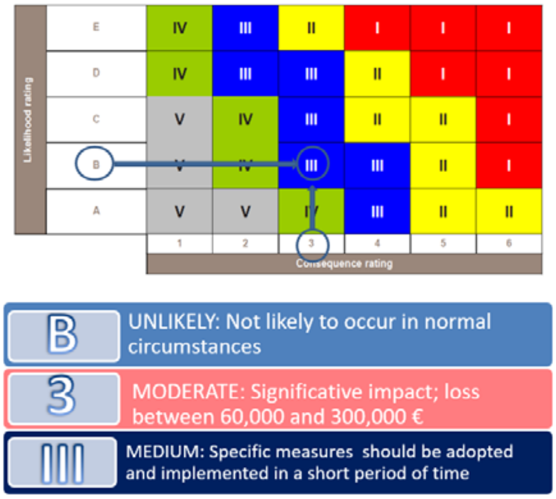


Figure 2-63. Risk evaluation of sinkholes for the three Stages

Proposed treatments for sinkholes

To minimize the existing risk for buildings located in the zone of potential impact of linear discontinuous deformation, in the area of the flooded Anna mine, it is necessary to take steps to detailed inventory of old shallow excavation and then to backfill them to increase their stability.

For this purpose it will be necessary to perform appropriate geophysical surveys, specific drills etc. to determine approximately the shape, volume of voids and its localization.

If newly designed buildings are taken into consideration, it is necessary to introduce information on the possibility of discontinuous deformation occurrence in such area in the land use plan. This information will allow for a partial limitation of the development of this area or the need to protect buildings against discontinuous deformations like grillage foundation, reinforced concrete foundation slab.

CANDÍN MINE

Risk identification

The risk identification is the same as in Anna mine. In the case of Candín, only one stage was considered, which is the flooding of Candín mine to the depth of 174 m.a.s.l. This is the level to which water is allowed to reach without producing undesired superficial flooding effects.

Risk analysis of uplift

To assess the risk associated with ground surface continuous deformation, the deformation indicators have to be estimated, i.e. uplift (vertical deformation). The analysis considers flooding of the Candin mine to the depth 174 m.a.s.l. Predicted uplift for Candin mine obtained using Sroka's method is presented in Figure 2-64.

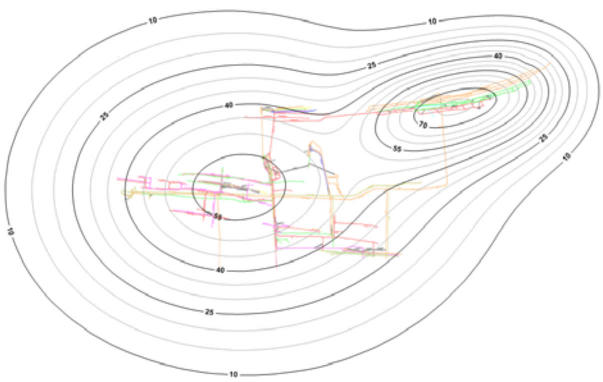


Figure 2-64. Predicted uplifts for Candín mine

The flooding analyses have been performed using two methods. Simulations have been carried out using analytical Sroka's method and numerical method using change of bulk density, which has been proposed by the authors.

In first method, maximum vertical displacement approx. 80 mm has been obtained. Calculations using numerical method showed a similar value to one from the analytical method, which was approx. 81 mm.

Risk evaluation for uplift

As it has been mentioned in risk identification part, the only stage of hazard for Candin mine applies to flooding the whole mine.

After precise familiarizing with the properties of the rock mass, among others with the existence of natural cracks, voids, layering etc. and using the obtained results of the analyses it was assumed with high probability that flooding the Candin mine region in accordance with the assumptions of Hunosa mining company will not lead to visible effects on the ground surface.

The authors’ experience in the field of rock mass deformations caused by the mine flooding and analyses, which have already been presented in the created reports, show a small risk of damage to buildings on the ground surface and hazards related to environment by continuous deformations.

The maximum values which have been obtained during the simulations using analytical and numerical methods were close to 80 mm.

Taking into account other deformation indicators, such as e.g. angle of range influence, which is very flat in flooding phenomenon (approx. 10 degrees), and therefore area of heave is very large with low values of uplift and tilt.

In such cases the risk of visible hazards and damages to structures on the ground surface is low for stage 1, when only continuous deformations are taken to consideration.

The results obtained by applying the proposed methodology of risk assessment are presented in Figure 2-65.

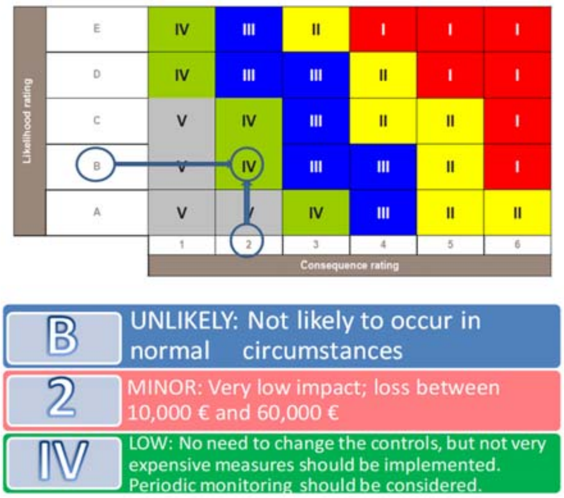


Figure 2-65. Risk evaluation for uplift

All the rest of the analysis was the same as in the Anna mine case study.

T3.2 Groundwater risk assessment at the selected PGG and HUNOSA mines (UNIOVI, GIG, IMPERIAL, HUNOSA, PGG)

The main objective of this task was to evaluate the risk identification, evaluation and prioritisation of areas exposed to groundwater risk at the selected PGG and HUNOSA mines.

RYDUŁTOWY-ANNA MINING COMPLEX (POLAND)

Risk identification

For the case of Rydułtowy-Anna Mining Complex, the risk assessment has focused on the groundwater chemistry. This has helped evaluate the magnitude and extent of any potential groundwater pollution around the mine sites.

As the mine hydrochemistry has shown heavy metal concentrations below the detection limit, the substances to be focused for risk assessment and for which potential risk may occur were selected as acid mine drainage (iron and manganese), sulphates and chlorides.

Any interaction/communication with other mines, such as Anna with Rydultowy mine, that inflows from each mine could be transported to one level and pumped to the surface; and with other aquifers where different water bodies with different composition could mix together, could also lead to groundwater vulnerability and therefore to groundwater pollution.

Risk analysis

Iron is an important source of mine water pollution. Fixed PNEC thresholds have been established, based on chronic and acute ecotoxicity databases and different derivation approaches to represent the toxicity of iron:

- PNEC long-term: 16µg/lt (TGD deterministic approach based on 3 species)
- PNEC short-term: 41µg/lt (TGD deterministic approach)
- PNEC long-term: 186µg/lt (MANAGER probabilistic approach from SSDs)
- PNEC short-term: 887µg/lt (MANAGER probabilistic approach from SSDs)

For Anna mine, only location PS1 of mine water discharge and PS3 of industrial sewage discharge, with concentrations 49 µg/lt and 160 µg/lt respectively, failed to reach the PNEC short-term (PS1) and long-term (PS3).

The sulphate, sodium and chlorides content as well the Electrical Conductivity (EC) of the mine groundwater were very high, indicating an unsuitable water for use without any treatment before. Figure 2-66 presents the chloride concentrations measures in discharge points versus different standards.

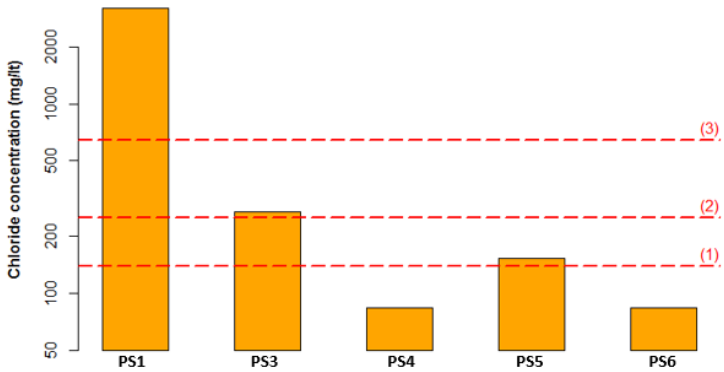


Figure 2-66. Chloride concentration measures in discharge points versus (1) PNEC long-term, (2) Drinking standard, and (3) PNEC short-term

The surface aquifer developed to evaluate potential surface water/aquifer contamination risk around the Rydultowy-Anna mining complex when the Rydultowy colliery is also abandoned and pumping is terminated considered the Leon II, III and IV shafts (Figure 2-17) as a potential point source for contaminant release in the area.

Initially, a conservative solute transport model was implemented to assess contaminant transport path in the surface aquifer. A high fixed concentration value (1,000mg/l) of a nominal contaminant during the transport modelling was assigned at the shafts. The spread (transport) of this contaminant along the groundwater flow direction was simulated for over a period of 50 years. The simulation results showed that the contaminant would be transported, and diluted along the way, over a distance of approximately 1,500 m in 30 years, and further to around 2,000 m in 50 years. The simulation results after 30 years are presented in Figure 2-67. GIS raster files were prepared in ArcMap accordingly to show the contaminant transport over the simulated period.

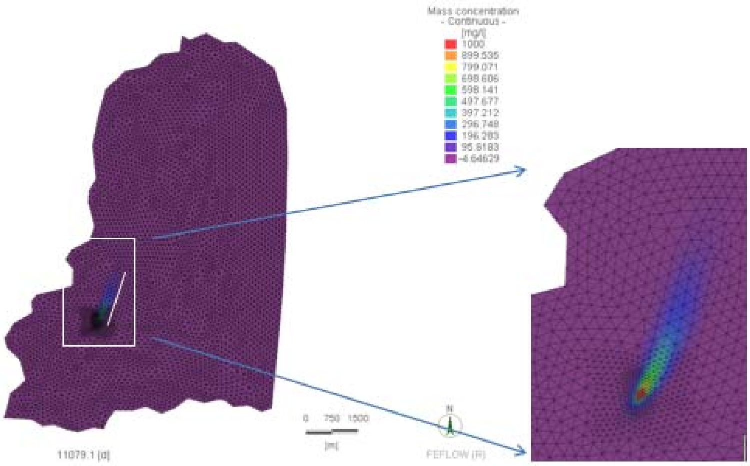


Figure 2-67. Simulated contaminant concentration at the surface aquifer base after 30 years

Next, multispecies solute reactive transport simulation to represent processes related to acid mine drainage were carried out to simulate the fate of the groundwater reactive contaminants in the surface aquifer. This was achieved by coupling PHREEQC and FEFLOW, carried out through the piChem plugin for FEFLOW. The reactive transport modelling focused on the contaminants Cl, SO_4, Fe and Mn, which are the typical acid mine drainage components, as they are being transported in the surface aquifer. A PHREEQC input file for both inflow boundary and initial conditions was assigned based on the discharge water composition for the sampling locations PS1, PS5 and PS6 around the mining complex (Figure 2-48). Reaction steps were calculated for every transport step, at 30 and 50 years.

The simulation results showed that the contaminants, Cl, SO_4 and Mn, had adverse effects in the shaft location in terms of irrigation and drinking purposes for the first year. The contaminants would be transported, and diluted along the way throughout the 30 and 50 years, with no effects along the pathway. The results for the contaminants Cl aftee 30 years and SO_4 after 50 years are illustrated in Figure 2-68. GIS raster files were prepared in ArcMap accordingly to show the contaminant transport over the simulated period.

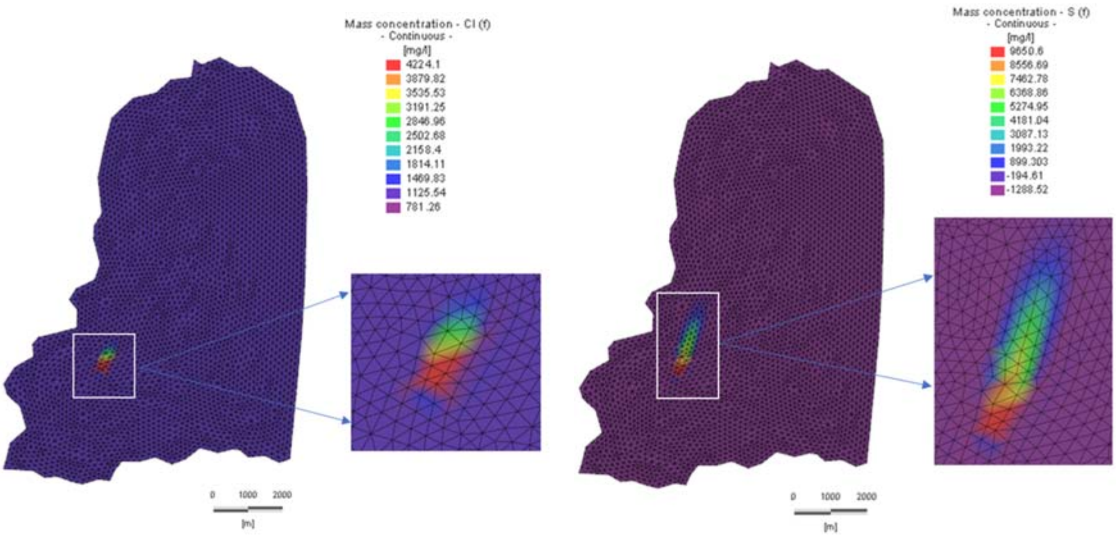


Figure 2-68. Reactive transport modelling results for (a) Cl after 30 years, and (b) SO_4 after 50 years

Risk evaluation

A risk index for all the identified contaminants were produced, based on the established risk criteria and the transport model to determine the consequence/probability of any adverse effect and where additional action is required. The risk analysis for the Cl, SO_4 and Mn is obtained for the first year by applying the methodology of risk assessment. Likelihood was rated with an "E", as the impact is quite certain to happen. Therefore, the risk would be high and strong measurements need to be adopted and implemented (Figure 2-69).

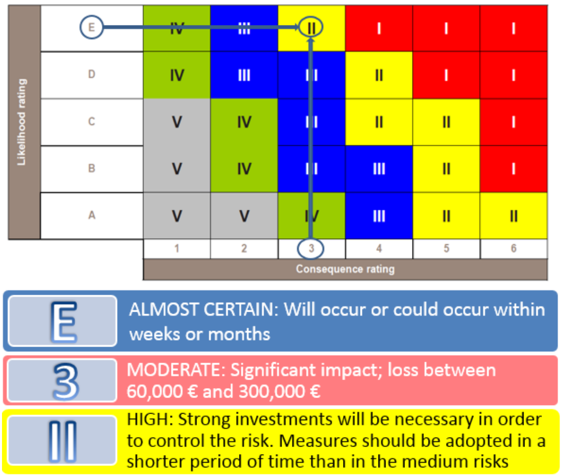


Figure 2-69. Risk analysis for groundwater pollution around Rydułtowy-Anna Mining Complex

Proposed treatments

Passive in-situ remediation using permeable reactive barriers (PRBs) is considered as a promising technology for effective groundwater remediation. PRB is an in situ permeable treatment zone filled with reactive materials, designed to degrade or immobilise and remediate a contaminant plume under natural hydraulic gradients. The contaminants are removed from the groundwater by geochemical processes.

PRBs are typically constructed perpendicular to the flow of groundwater. When the contaminated water passes through the PRB, contaminants are either immobilised or chemically transformed to a less toxic state by the reactive material contained within the barrier.

It was estimated that the total cost of a PRB system may be at least sixty percent cheaper than the equivalent pump-and-treat system. For example, depending on the site size and complexity of a PRB system, it could cost up to €450,000, versus the cost for a pump and treat remediation, reaching up to €6.3 million.

MOSQUITERA AND PUMARABULE MINES (SPAIN)

Risk identification

The aim was to generate a comprehensive list of risks based on those events or effects that might create, enhance, prevent, degrade, accelerate or delay the achievement of objectives that were established in the context.

The events or effects that have to be considered based on the established context were floods, pollution of underground aquifers and flooding of other mines.

When analysing the floods effect, three different sub-effects were considered together in the analysis: modification of flows, appearance of humid zones and floods (violent or not), as all of them imply an undesired flooding level of the mine water. Two causes were finally considered: extremely heavy rain and pumping failure. In the case of the pollution of underground aquifers effect, the cause identified was the interaction with other aquifers, and in the case of flooding with other mines effect, the causes were: interaction with other mines and artificial communication with other mines.

Risk analysis for floods

In order to analyse the risk of extremely heavy rain, first the pumping system that is installed in the shafts was studied. Five pumps were installed in the shafts (three 37 kW pumps with a nominal flow of 225 m^3/h each in Mosquitera, and two 55 kW pumps with a nominal flow of 240 m^3/h each in Pumarabule) to maintain the security level (Figure 2-70).

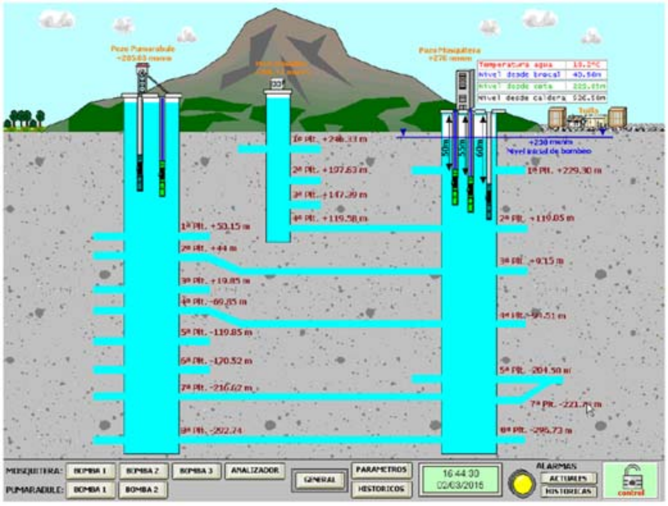


Figure 2-70. Installed pumping systems in Mosquitera and Pumarabule Mines

Pumarabule is used as an auxiliary pumping facility for Mosquitera, so in Pumarabule there is pumping only when Mosquitera pumps are not able to maintain the flooding level.

In order to determine the water balance of the area appropriate hydraulic limits were defined as well as the potential surface discharge areas.

The capacity of pumping facilities to remove the necessary volumes has been proven satisfactory. However, it has been recognized and evaluated the potential surface discharge area.

Results of inundation risk were analysed in terms of groundwater flooding, which occurs when the water table in permeable rocks rises above the ground surface. The very low permeability of the carboniferous unaltered massif reduces the possibility of groundwater flooding. Actual water level (235 m.a.s.l.) is above the shallower mine floor of Mosquitera (229 m.a.s.l.) but under the first floor of Pumarabule (250 m.a.s.l.) and Rosellón (246 m.a.s.l.) mines.

Thus, it was evaluated also a potential risk accounting for a sudden rise of water level in the shafts, that would be critical, as no buffer volume such as an intermediate unflooded floor would be available in Mosquitera to impede fast discharge to the surface.

Risk evaluation for floods

To evaluate the possible influence of water levels in the mine kept at an elevation of 235 m.a.s.l., the probability of occurrence of groundwater levels above selected surface elevations has been calculated.

Likelihood was rated with a "C", as floods caused by extremely heavy rain may occur at some time but they are not expected to occur regularly under normal circumstances. In case that a modification of the river flow or an uplift of the river happens, the impact will be moderate (monetary loss can be estimated between 60,000 € and 300,000 €), and thus specific measures should be adopted and implemented in a short period of time (Figure 2-71).

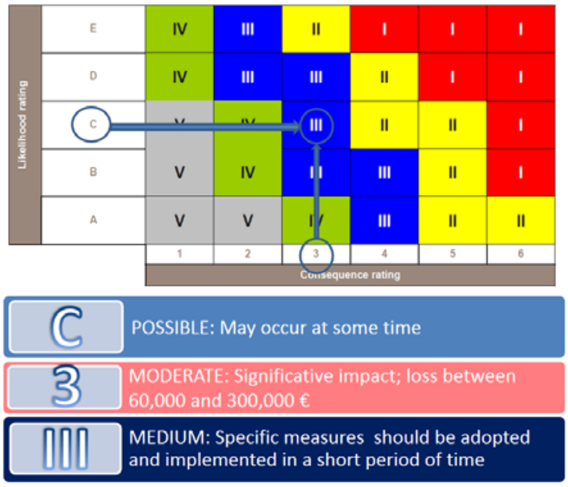


Figure 2-71. Risk evaluation for floods

Proposed treatments for floods

To develop additional piezometric controls in the area with higher risk of floods, especially south of Tuilla, near Mosquitera 2. The reason is that the two piezometers already installed are in a more elevated area, in the quaternary deposits near Mosquitera 1, showing no connection with the Carboniferous aquifer, therefore being perched aquifers not included in the conceptual model.

Also, to install independent powered water level alarm sensors in those piezometers, ideally connected by phone with the person in charge of the pumping system, something that will complement these specific measures.

Finally, with the use of these piezometers, time-series of pumping rates and levels in the mine should be provided with higher sampling frequency (i.e. diary better than monthly), as the estimation of recharge values are of extreme importance to assess the infiltration to the aquifer and relate head variations with rain data.

Also, the installation of at least one weather station (which is relatively cheap) providing daily data of rain and temperature on the study area would provide advantageous information that could be linked to high-frequency series of pumping/levels in the mine.

Risk analysis of pollution of aquifers

Regarding the pollution of aquifers, there is only one water point close to the study area in which the interaction with the mine water should end in pollution.

Likelihood was rated with an "E", as the impact on the water point it is quite clear to happen.

On the other hand, as the water from this water point is used for industrial purposes, the impact will be very low (monetary loss can be estimated between 10,000 € and 60,000 €), but specific measures should be adopted and implemented in a short period of time (Figure 2-72).

Proposed treatments for pollution of aquifers

The specific measure to adopt is to undertake a hydrochemical laboratory control analysis and head monitoring at the water point, as it corresponds to a pit with gallery which elevation is below the security level (200 m) so there is a possible flow from the mine, and it is used by industry. The periodicity of the controls or the possibility to stop them will depend on the characteristics of the water required by the industry, something that will have to be evaluated.

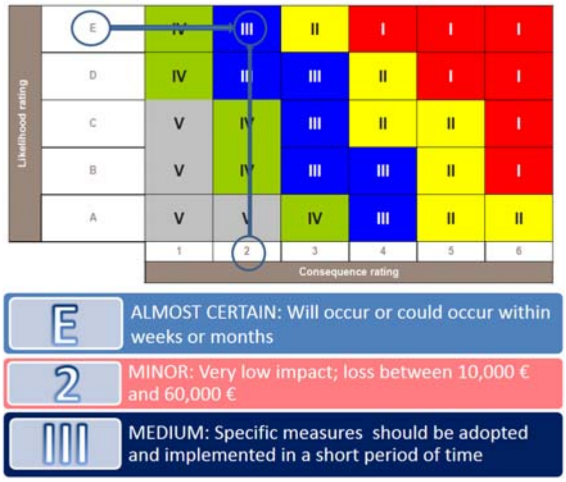


Figure 2-72. Risk analysis of pollution of aquifers

Risk analysis for flooding of other mines

Three mine systems in the area are close to Mosquitera and Pumarabule Mines. To the Northeast, the mines of Toral-Aramil and Lieres, to the Southwest the mine of Candín and to the Southeast the mine of Venturo. Toral mine is relatively small and at higher topographic height so influence from or to Mosquitera and Pumarabule Mines is not expected. It is connected with another small mine, Aramil, located to its Northwest.

Figure 2-73 shows a schematic cross-section (not to scale) representing the actual different stages in Venturo (and Sotón) mines, with water levels still depressed, and Mosquitera, where water level has almost completely recovered. A hydraulic gradient from Mosquitera to Venturo-Sotón is assumed, however, a very low permeability would mean a very low water flow.

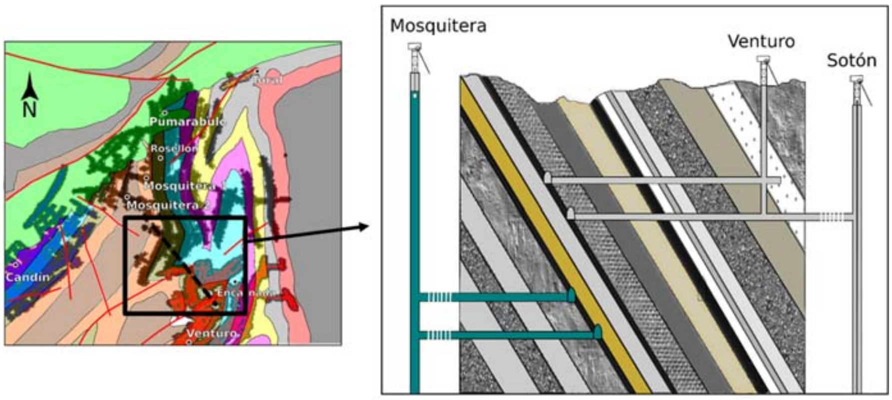


Figure 2-73. Schematic cross-section showing the different flooding stages of Mosquitera and Venturo-Sotón mines. Scales not real, scheme just interpretative

Likelihood was rated with an "A", as it is very improbable that communications between isolated mines occur, moreover if we take into account that the massif has very low permeability. On the other hand, the consequence rating was rated as "minor" or with a very low impact as in case that a communication finally happens the problem will be solved with the installation of a pump and its system control (Figure 2-74).

The consequence was not rated as "insignificant" because Sotón is the mine that Hunosa uses for touristic visits in its 8th, 9th and 10th floors and, in case that something happens, safety reasons will force to stop all the visit programmes until the situation will be completely under control.

Figure 2-74. Risk analysis for flooding of other mines

***T3.3 Surface water pollution risk assessment at the selected PGG and HUNOSA mines (IMPERIAL**, *UNIOVI, PGG, HUNOSA*)**

The main objective of this task was to undertake a risk evaluation based on the results from the T2.3 in WP2. The estimates of metal speciation from the surface water chemical speciation modelling (Task 2.3) were used to determine the potential risk for the surface water physic-chemical parameters to aquatic biota.

RYDUŁTOWY-ANNA MINING COMPLEX (POLAND)

Risk identification

For the aquatic toxicity assessment, as a first step, hazards and sources of harm were identified. Environmental quality standards together with the environmental exposure (actual measured) concentration are used in this step to screen for contaminants present and detect if any of them may pose an environmental risk.

The substances found in the discharged water, for which potential risk may occur, are copper, zinc, lead, manganese, chloride/sodium, sulphates and iron. Due to their chemical and biological character, they may result in adverse biological effects on organisms (i.e. reproduction, growth, mortality) and hence to poor ecological status.

Direct discharges from the mine were identified as source of contaminants. The contaminants are then transferred to surface water, where they are taken up by aquatic organisms e.g. into gills or leaves, cells, as a result affecting the aquatic ecosystem adversely.

Besides the concentrations of individual contaminants, the assessment for surface water hazard also needs to take into account the physic-chemical parameters of the surface water. Sampling locations were selected close to the mines and include upstream, downstream and effluent discharge points.

Risk analysis

To assess the risk associated with surface water discharge, the bioavailable metal concentration was analysed including exposure and effect assessment steps.

The assessment of exposure considers the concentration of the substances present in the environment. Subsequently, the assessment of the effects defines the extent that target organisms may be exposed to the contaminant.

As the first step, the exposure assessment identifies the amount of hazardous substance that might reach a susceptible target population, given the physic-chemical parameters of surface water which might influence the level of exposure. The value is commonly known as the Predicted Environmental Concentration (PEC).

In the second step, the effect assessment is based on determining the ecotoxicological effects (NOEC) and is based on an appropriate method (probabilistic, algorithm, BLM), which allows the determination of the Predicted No Effect Concentration (PNEC). This value constitutes a protective concentration (a threshold for the acceptability of risk) for each contaminant.

A user-friendly bioavailability tools approach M-BAT for Cu, Zn, Pb and Mn was used. It requires the input of a small number of abiotic water parameters: pH, Ca and DOC to determine the PNEC value for the sampling locations, aiming to identify which sites may be at low or high risk of EQS failure. The M-BAT bioavailability tool is run to calculate the site-specific No-Effect and bioavailable concentration for each of the selected metals, assess compliance with a bioavailable EQS and estimate the potential sensitivity of waters to metal inputs, based on local water chemistry conditions.

At Rydułtowy-Anna Mining Complex (Poland), the majority of samples exceeded the bioavailable concentration for zinc, which could indicate a potential adverse effect. For manganese and lead, there is only one water location where the risk ratio is higher than 1, indicating that further investigation is needed.

An important advantage of this approach is that the calculation of PNEC, the protective concentration for each substance, is determined with reference to the whole ecological community using the Species. Using the Species Sensitivity Distribution, the 5th percentile value is then specified (HC5-hazardous concentration). This benchmark of effects represents a value at which 95% of the species in an ecosystem are assumed to be protected against the adverse effects of the metals studied.

The Cu, Zn and Pb Species Sensitivity Distributions have been structured for the different sampling locations both mines. The zinc SSDs for PS6 (Rydułtowy-Anna Mining Complex) is presented in Figure 2-75.

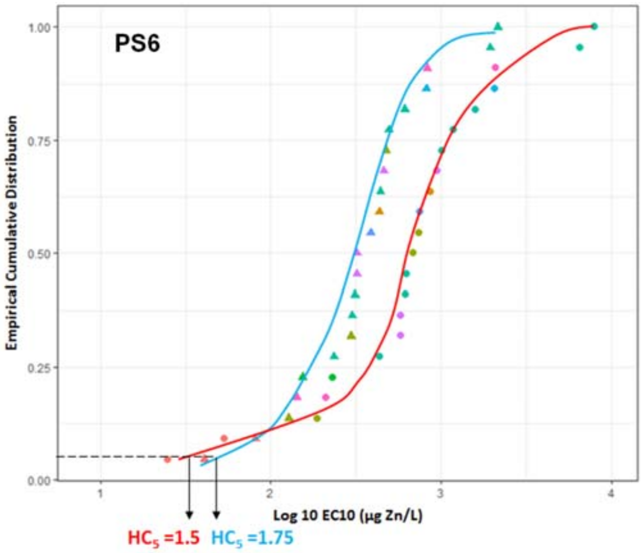


Figure 2-75. Zinc SSDs for PS6 (Rydułtowy-Anna Mining Complex mine)

The physicochemical parameters at the different locations and changes in these observed over time have shown to have an influence on the no-effect concentration and hence on the HC5 concentration of the heavy metals. The outcomes from the exposure (metal concentration) and effect assessment (HC5-SSDs) are integrated into the risk ratio to describe the magnitude of the risk posed by the tested chemical. The risk ratio for copper and lead was low (less than 0.30).

However, the highest zinc index at Rydułtowy-Anna Mining Complex occurred at the locations of purified rainwater discharge from Leon IV shaft (PS6 with a ratio at 1.01) and industrial sewage discharge to Syrynka stream at Ryszard point (PS4 with a ratio of 0.8). Mine water discharge to Nacyna River (PS1) had an elevated risk index at 0.56. Such indices suggest that a negative impact of this metal for the aquatic ecosystem may occur. There is therefore a need to take measures to reduce the environmental risk present for zinc.

As iron is also an important source of mine water pollution, it has been considered in the risk analysis. Fixed PNEC thresholds have been established, based on chronic and acute ecotoxicity databases and different derivation approaches to represent the toxicity of iron.For Rydułtowy-Anna Mining Complex, only location PS1 of mine water discharge and PS3 of industrial sewage discharge, with concentrations 49 μg/lt and 160 μg/lt respectively, failed to reach the PNEC short-term (PS1) and long-term (PS3).

High levels of chlorides can also make it difficult to achieve good or moderate ecological status in rivers. Chloride concentrations for different discharge locations at Rydułtowy-Anna Mining Complex and the corresponding quality standards were presented in Figure 2-66. At Rydułtowy-Anna Mining Complex, the majority of the samples exceeded the threshold values for Chlorides, which may induce indirect effects on the aquatic ecosystems and drinking water quality.

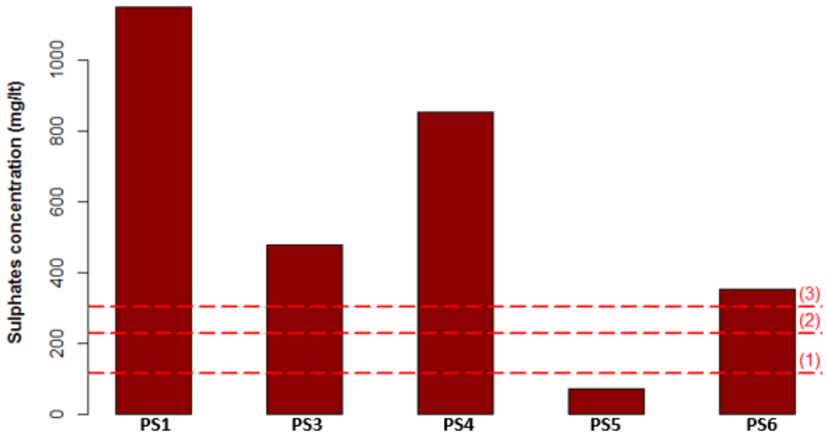


Figure 2-76. Sulphates concentration measures in discharge points versus (1) PNEC long-term, (2) Drinking standard, and (3) PNEC short-term

Finally, sulphates can also have adverse effects on aquatic ecosystem, when elevated, affecting eutrophication and causing concerns for human health when water is used for drinking. Similar to chlorides, the majority of samples at Rydułtowy-Anna Mining Complex exceeded the sulphate thresholds values in terms of both the no-effect concentration for the aquatic ecosystem and the drinking water standards.

Risk evaluation

The chemical and aquatic toxicity risk analysis results were used to produce a risk index for each particular contaminant, allowing to compare the results with established risk criteria and determine the consequence/probability of any adverse effect and when additional action is required.

For Rydułtowy-Anna Mining Complex, the risk associated with copper and lead is low and hence, there is no need to take action to minimise the risk. The same risk likelihood applies for the zinc risk analysis for PS3 and PS5 locations at Rydułtowy-Anna Mining Complex.

However, for PS4 (risk index= 0.78) and PS6 (risk index= 1.0) for zinc and for PS1 (risk index= 1.0) for manganese at Rydułtowy-Anna Mining Complex, there is a likelihood for potential risk to occur if conditions change; and although the risk is low, occasional monitoring should continue (Figure 2-77).

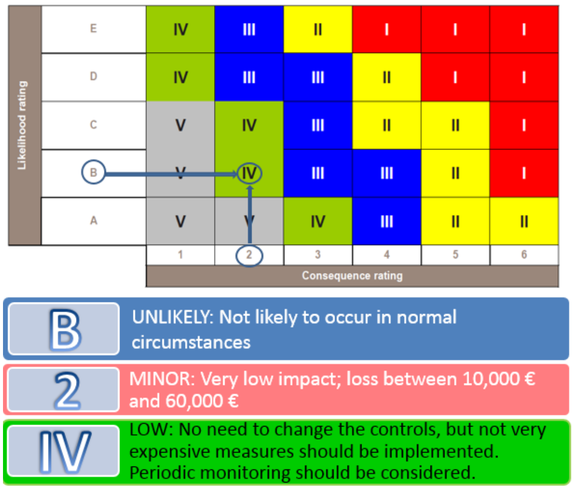


Figure 2-77. Risk evaluation for zinc (PS4 and PS6) and manganese (PS1)

Although there is no potential risk associated with heavy metals, there is risk associated with iron concentrations (Figure 2-78).

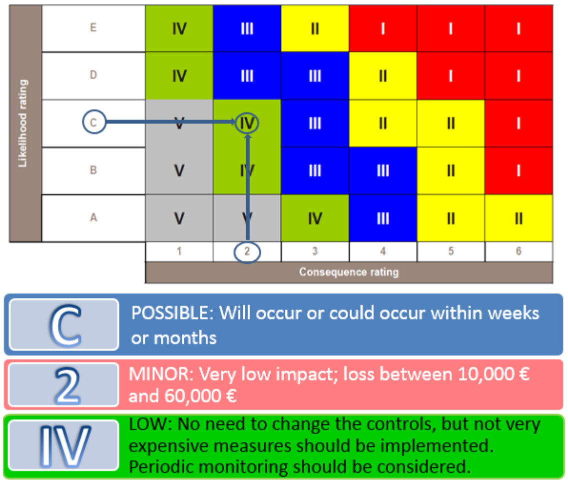


Figure 2-78. Risk evaluation for iron

Similarly, for chlorides, the risk matrix for PS1 (mine water discharge) at Rydułtowy-Anna Mining Complex is presented in Figure 2-79.

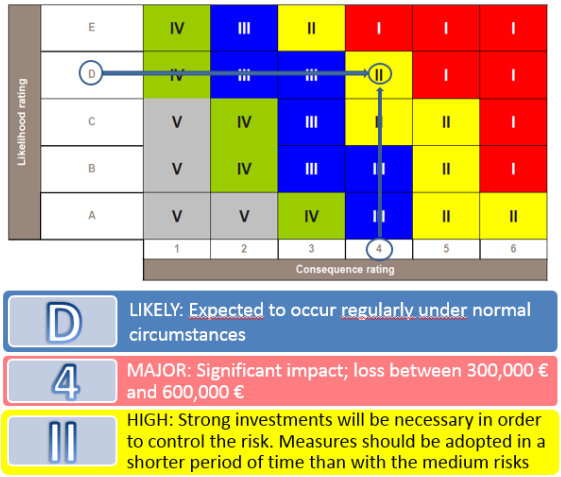


Figure 2-79. Risk evaluation for chlorides in PS1

Additionally, the risk for chlorides for PS3 industrial sewage discharge at Rydułtowy-Anna Mining Complex is medium and some additional measures need to be considered.

Finally, sulphates risk matrix is presented in Figure 2-80, relevant for the majority of the sampling locations as all of them failed the PNEC and the drinking water criteria, especially the PS1 and PS4 samples.

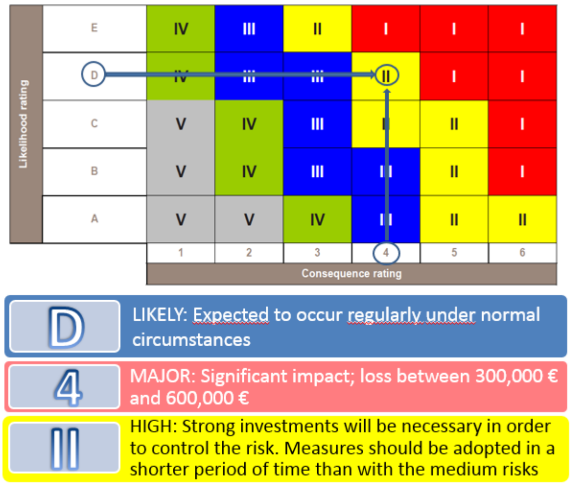


Figure 2-80. Risk evaluation for sulphates

Proposed treatments

For the risk associated with iron, passive treatment systems are a preferable option for treating acid mine drainage for closed mines.

They are relatively recent technology that involves benefitting from the advantages of passive treatment systems; namely that they: do not require electrical power, any mechanical equipment, no hazardous chemicals, or buildings, nor daily operation and maintenance care; are more natural and aesthetic in their appearance, may support plants and wildlife and are less expensive.

For the risk associated with sulphates, the Cost Effective Sulphate Removal (CESR) process removes high concentrations of sulphates through addition of hydrated lime ($Ca(OH)_2$), which precipitates calcium sulphate, being a good option.

Finally, for the risk associated with chlorides, vacuum evaporation is a clean, safe and a versatile technology, which has a very low management cost. It transforms waste effluent into two streams, one of concentrated waste and another of high-quality water.

The evaporators work under vacuum, so the boiling temperature of the liquid effluent is lower; thus saving energy and improving efficiency. The equipment is compact and so the operational monitoring is simple, allowing effluent flows of up to 20 m^3/h to be treated in a single evaporator. As the effluent does not need to be heated at high temperatures, as the water boils at 35-40°C when working under vacuum, the energy requirements are lower.

MOSQUITERA AND PUMARABULE MINES (SPAIN)

Risk identification and risk analysis are the same than for Rydułtowy-Anna Mining Complex.

Risk evaluation

For Mosquitera and Pumarabule Mines region, the risk associated with copper and lead in surface waters is low and hence, there is no need to take action to minimise the risk. The same risk likelihood applies for the zinc risk analysis for the upstream water sampling locations at Mosquitera and Pumarabule Mines region, as well as for chlorides. Also, for the zinc concentrations at effluent discharge, no specific action is required.

Although there is no potential risk associated with heavy metals, there is risk associated with iron concentrations (Figure 2-81).

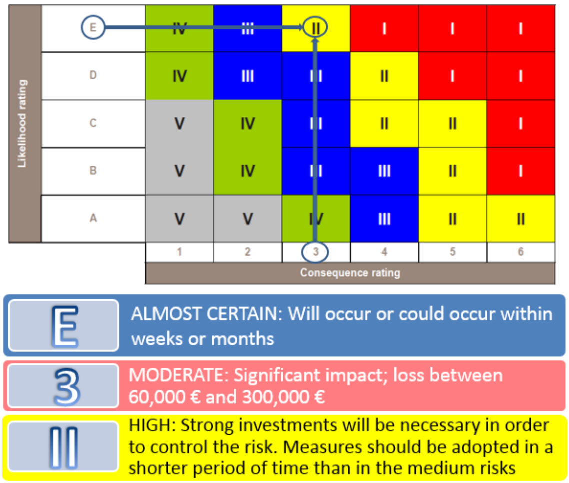


Figure 2-81. Risk analysis for iron at Mosquitera and Pumarabule Mines

Finally, sulphates for the downstream and effluent discharge samples present also a high risk, with likelihood rated "D", and a major impact.

Proposed treatments

To minimise the risk associated with the surface water pollution in terms of iron and sulphates, specific actions need to be adopted.

The same treatments that were proposed in Rydułtowy-Anna Mining Complex for iron and sulphates, are proposed here.

T3.4 Gaseous emissions risk assessment at the selected PGG and HUNOSA mines (Ineris, *IMG-PAN, GIG, PGG, HUNOSA)*

The main objective of this task was to propose an approach for gas risk management at the surface closed to coal mines, easily adaptable to all European countries.

ANNA MINE (POLAND)

Risk identification

The hazard associated with the emission of gases to the surface during and after a mine closure depends mainly on the intensity/amount of the gases in mine workings and the occurrence of structures and places which enable migration of the gases to the surface. The situation looks similar for the emission of gases to another mine.

The assessment of voids where methane will get collected ought to consider the volume of mine workings and the volume of consolidated longwalls. For partially flooded mines, the effects of flooding voids, i.e. a decrease in their volume and a decrease in methane emission from goafs, ought to be considered.

The areas where gas emission to the surface can occur are the places where mining operations were conducted close to the surface, the areas affected by faults and the areas of closed shafts.

Risk analysis

The volume of emitted methane is a parameter which can be assessed following the model of methane emission from longwall goafs after concluding mining operations. Thus, the amount of the gas emitted from the goafs was estimated, concerning a period of 15 years after the mining operations in the last longwall stopped. This estimation included all the longwalls in Anna mine; also, the influence of partial flooding of the goafs was considered.

The total volume of methane emitted from goafs between 2018 (after closing the shafts and separating the ventilation system from active Rydułtowy mine) and 2031 (the end of methane emission) will be 11 524 262 m^3.

To assess the volume of voids, the volume of mine workings was calculated considering their reconsolidation depending on the method of closing longwalls. For the longwalls with roof caving it was 0.1, and for the longwalls with backfilling, the index was 0.02. The volume of voids calculated in such a way considers the change caused by water inflow. According to the calculations, by the end of 2020, the inflow of water should stabilise.

The water flowing into the closed mine workings will overflow into the mine workings of Rydułtowy mine, and then it will be pumped, thus, in the following years there will not be any changes in the volume of voids in the closed mine.

The process of methane emission from goafs and the process of changes in the volume of voids will have an influence on the change in the concentration of methane in the voids of closed Anna mine.

As both the amount of emitted methane and its concentration influence the risk posed on the surface, the calculations were conducted following the gas model proposed in the task 2.4. The calculations show that the concentration of methane in mine voids during shaft closing is approx. 8% CH_4 and exceeds the lower explosive level (4.5% CH_4).

Such a concentration of methane in the area of a shaft during its closure results in high probability of an explosion. As the methane concentration will not be uniform in the mine workings (voids) it is necessary to identify the places of high concentration of methane through the simulations (Figure 2-82).

Relating to the emission of gasses by different places than the shafts, due to the presence of faults in the area, permeability of Carboniferous overburden located above the faults was analysed.

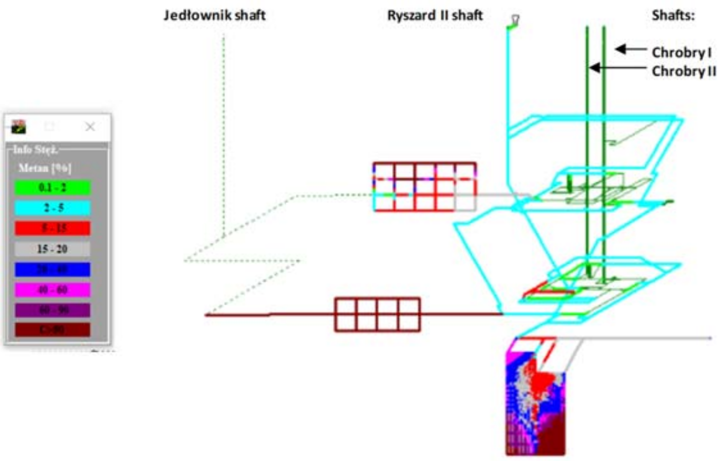


Figure 2-82. Simulation distribution of methane concentration in former ventilation network and goafs with VentGraph-Plus

The analysis showed that in the area only virtually impermeable and low-permeable geological formations (impermeable and low-permeable layers) are present. As a result of the above evaluation and analyses of the gas, risk in the area of the Jedłownicki drift was determined to be low (Figure 2-83).

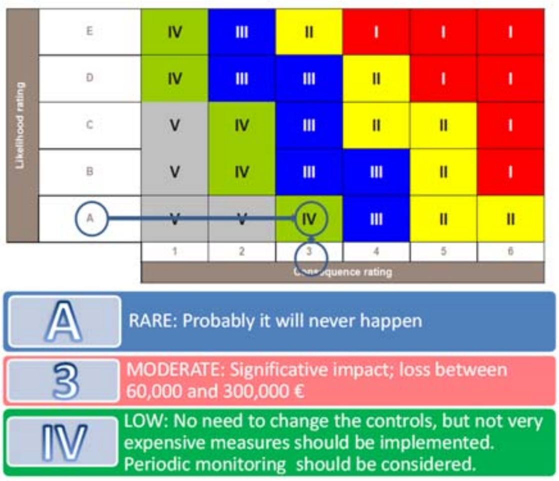


Figure 2-83. Risk evaluation of gas migration to the surface

Gas migration risk and gas explosion risk for the area of Jedłownicki drift connecting Jedłownik shaft with the mine workings of Anna coal mine is low. Lowering the risk level will concern only the areas of shallow exploitation and shafts marked red and yellow (Figure 2-84).

Proposed treatment

Depending on the results of measured methane concentrations in the shaft and gas pressure, flares, gas vents or gas engine may be used.

To minimise the explosion risk for the area of Ryszard II shaft it is necessary to prohibit construction of buildings within 20 metres of the closed shaft. In the area of shallow exploitation, it is necessary to demarcate a zone expanded by 20 metres of the border of shallow exploitation and to make it obligatory to apply gas leak detectors in basements of the buildings located there.

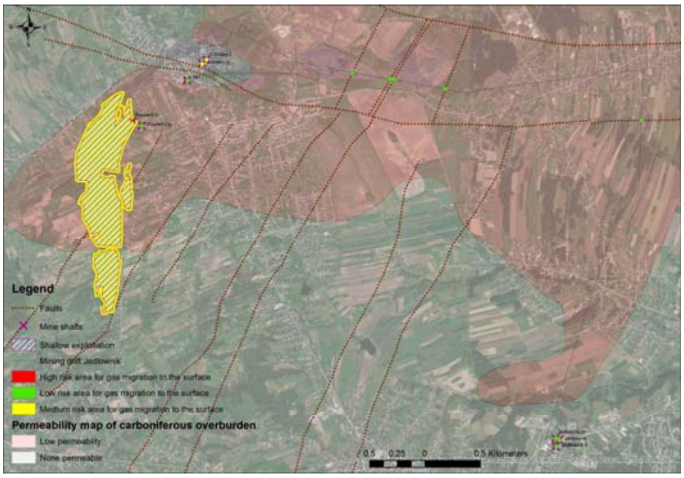


Figure 2-84. Medium risk area for gas migration to the surface

SANTIAGO-SAN ANTONIO MINES (HUNOSA)

Risk identification and risk analysis were similar to the ones developed for PGG mines.

Risk evaluation

Due to the fact that the closure process in Santiago mine was not finished yet, the analysis of the gas hazard also includes an assessment of the risk of methane accumulation in the San Antonio and Santiago mines during the closure process.

The flow rate of a gas-air mixture and the distribution of methane in mine workings depend on a number of various factors and are determined by the performance of the main fan installed in the mine shaft.

When the fan is not working, the flow of the gas mixture depends on natural depression generated by the methane distribution in mine workings.

The interaction between the above-mentioned factors changes distribution of the concentrations of gases in goafs and mine workings in San Antonio and Santiago mines.

Results of the simulation for 2033 (the end of methane emission), are presented in Figure 2-85.

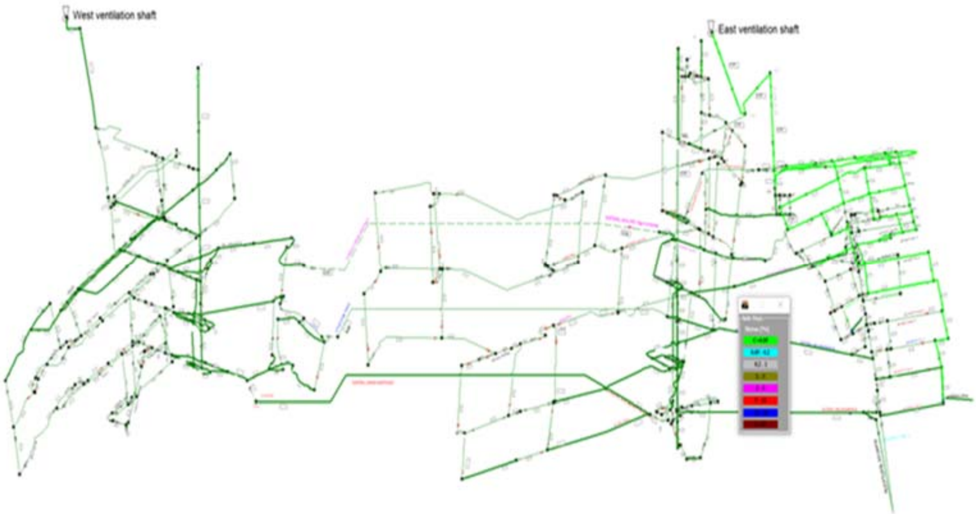


Figure 2-85. Simulation at the end of methane emission (2033)

According to the performed analysis, the consequences of gas emission will refer mainly to methane. The VentGraph-Plus simulation shows that the concentration of methane in the whole analysed area does not exceed explosion concentration (5%).

The results obtained by applying the proposed methodology of risk assessment are presented in Figure 2-86.

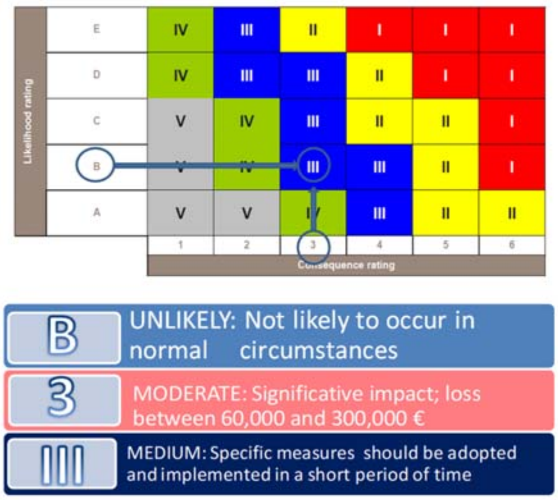


Figure 2-86. Risk evaluation for accumulation of gas in the mine during the closure process

Proposed treatment

To minimise the existing risk, it is necessary to take steps to provide continuous monitoring of methane concentration in the mine and the performance/status of the ventilation system. Currently, the analysed mines use the automatic gasometry system to monitor the gas hazard.

The personnel responsible for ventilating the mine work 24/7 and the ventilation system is monitored with a special software and flow sensors. Following the relevant legal regulations, in the areas where explosive atmosphere may occur, the intrinsically safe equipment is applied. In the mine workings explosion proof ventilation doors are applied.

RADON IN ANNA MINE AREA (POLAND)

Risk identification

The areas where radon emission to the surface and its penetration into buildings can occur are the sites where mining operations were conducted close to the surface, the areas affected by faults, areas of settlement and the areas of closed shafts. It is generally considered that the sites of the disintegration of the surface layers are places of higher radon potential.

The mining-induced dislocations and damages have a strong influence on the foundations of a building, creating cracks in floors and walls and can lead to gases exhalation to the atmosphere or to the buildings.

Other phenomena influencing radon migration are related to changes in the water table and resulting from them hydrological disturbances that are observed in post-mining areas and in areas where mines are in the process of liquidation.

Risk analysis

All problems, related to exposure to indoor radon in dwellings and at workplaces, and identification of so-called radon prone areas followed by recommendations for the Member States, are specified in mentioned below document:

Council Directive 2013/59/EURATOM on 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation. The 2013/59/EURATOM Directive (Chapter VI, art. 54) recommends as the national level for radon indoor concentrations at workplaces value not exceeding 300 Bq/m^3 (annual average activity concentration). The exact value is recommended for dwellings.

The Member States shall establish a national action plan addressing long-term risks for radon exposures in dwellings (article 103.1). In Poland so-called radon prone areas will be identified, based on calculated "radon index". Radon index depends e.g. on radon in soil gas concentration and soil (ground) permeability. In general, local geology of rock body is the most important factor, influencing the radiation hazard for inhabitants of the area.

Risk evaluation

Results of radon measurement in soil gas showed that in some places the values exceeded the limits used for radon risk evaluation e.g. 40,000 Bq/m^3 and 64,400 Bq/m^3 close to shafts *Powietrzny 3* and *Ignacy*.

In such a case the probability, that radon levels in homes may be elevated, increases. The measured value of radon in soil gas concentration above 40,000 Bq/m^3 suggests a classification of the site as a medium risk area.

The nearest buildings are located approx. 80 meters away from *Ryszard II* and IGNACY shaft. These are detached houses. The rest of the area is covered with vegetation mainly in form of meadows and trees. Based on EPA data (EPA's Assessment of Risks from Radon in Homes EPA 402-R-03-003.), the number of inhabitants who may get lung cancer as a result of exposure to radon and die annually in Rydułtowy city was estimated. The results obtained by applying the proposed methodology of risk assessment are presented in Figure 2-87.

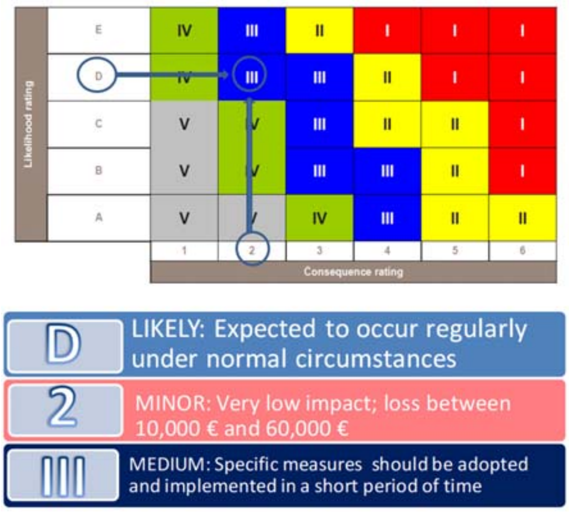


Figure 2-87. Risk evaluation for radon

Proposed treatments

Radon long-term monitoring, with use of nuclear track detectors is the appropriate technique to monitor the hazard in dwellings and workplaces.

To minimise the existing risk, it is necessary to perform measurements in soil gas in mining and post-mining areas.

The results are the basis for the risk classification of building sites. Depending on the class of risk, according to Neznal M. et al. (2004), specific mitigation methods should be performed.

Regarding results, different methods of radon gas concentration reduction can be proposed: increasing ventilation by opening windows more often; renovation works (sealing of cracks and fissure) in case of the presence of damages of walls and foundations, that open pathways for radon migration; for a certain group of buildings where the radon concentration increase will not be very high, using specialized building foils limiting penetration of moisture and gases (including radon) into the building would be recommended; and in cases of elevated or very high indoor radon concentration, it would be necessary to install fans and pumps for removing radon from inside buildings.

RADON IN MOSQUITERA AND PUMARABULE MINES AREA (SPAIN)

The same considerations apply to the radon in Spain.

In the areas of present and past mining activity, the important factor influencing the migratory ability of radon is the mining-induced transformations taking place in a rock mass.

In the area of investigation (Mosquitera and Pumarabule Mines area), coal mining generates considerable changes in rock mass, such as surface subsidence and tectonic discontinuities along fault zones).

Another phenomenon that might occur is the development of zones of cracks and fissures causing the disintegration of the rock body, which eventually enables the migration of gases. The mining-induced dislocations and damages have a strong influence on the foundations of the building, creating cracks in floors and walls.

Results of radon measurement in soil gas showed that in most area of interest radon in soil gas concertation did not exceed 10 000 Bq/m^3 which means that the risk is low.

However, in one specific location the measured value exceeded the limits used for radon risk evaluation e.g. 34,110 Bq/m^3 close to Mosquitera and Pumarabule Mines shaft location: the straight-line distance was 1.3 and 1.9 km respectively. In such a case the probability, that radon levels in homes may be elevated, increases.

The measured value of radon in soil gas concentration above 30,000 Bq/m^3 suggests a classification of the site as a medium risk area. In the area under consideration, a few residential houses are located at a considerable distance from the measurement sites.

Due to the low number of the results of field measurements, it cannot be excluded that similar radon in soil concentrations occur in close vicinity buildings.

Based on EPA data, the number of inhabitants who may get lung cancer as a result of exposure to radon and die annually in Mosquitera and Pumarabule Mines area was estimated.

Additionally, it was assessed the number of smokers, because risks associated with smoking and exposure to radon are synergic.

Due to low population, the total annual number of cancer cases and probable fatalities is much less than in case of Mosquitera and Pumarabule Mines area case study and does not exceed 1, including statistical number of smokers in the area.

During the period when the shafts are within the closing procedure, the pathways of radon migration are changed due to shafts backfilling. It may occur that in the areas near closed shafts radon emission increases.

If there are buildings near the closed shafts, radon penetration can be expected.

T3.5 Regional integration of different risk components (GIG, all partners)

RISK ANALYSIS

In the project, risk evaluation was done using a consequence/probability matrix or "risk matrix" where a subjective evaluation is made on the two dimensions of risk to give a "risk score" that provides overall priority, but not accurate risk acceptability guidance.

The consequence scale integrates a generic consequence based on the impact as well as an economic scale of losses used by insurance companies in the mining sector.

The scales and risk matrix to be used within the MERIDA project is presented in Figure 2-88.

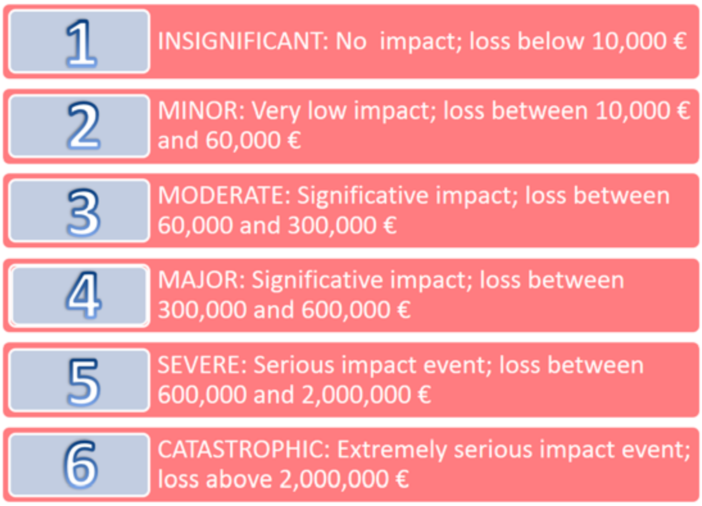


Figure 2-88. Scale of consequences according to the economic impact of losses as defined by mining insurance companies.

The probability scale needs to span the range relevant for the study in hand, remembering that the lowest probability must be acceptable for the highest defined consequence, otherwise all activities with the highest consequence are defined as intolerable (Figure 2-89).

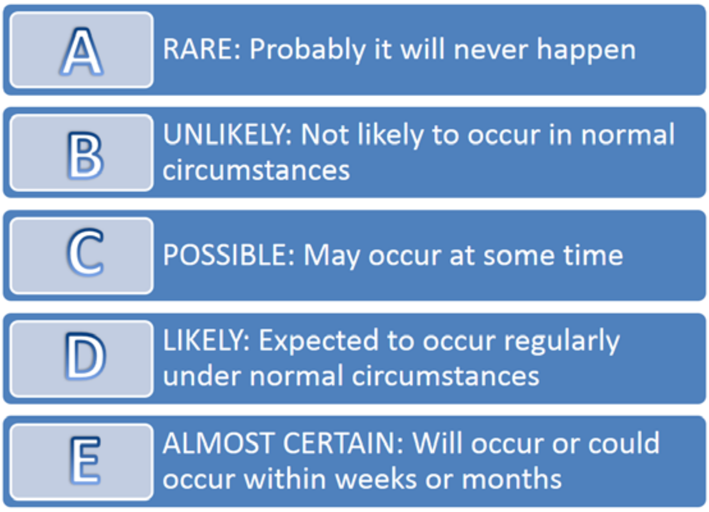


Figure 2-89. Likelihood rating.

After, a matrix is drawn with consequence on one axis and probability on the other (Figure 2-90).

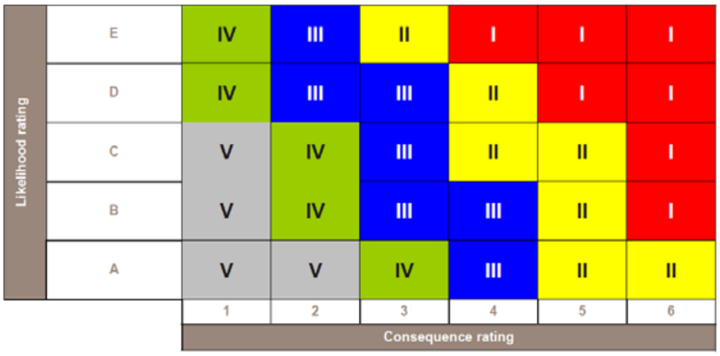


Figure 2-90. Risk matrix (IEC/ISO 31010, 2009).

The risk levels assigned to the cells will depend on the definitions for the probability/consequence scales. The matrix could be set up to give extra weight to consequences or to probability, or it may be symmetrical, depending on the application. In our case, the levels of risk are linked to decision rules: mainly the time scale by which response is needed.

Figure 2-91 presents the scale of risks that will be used in the project.

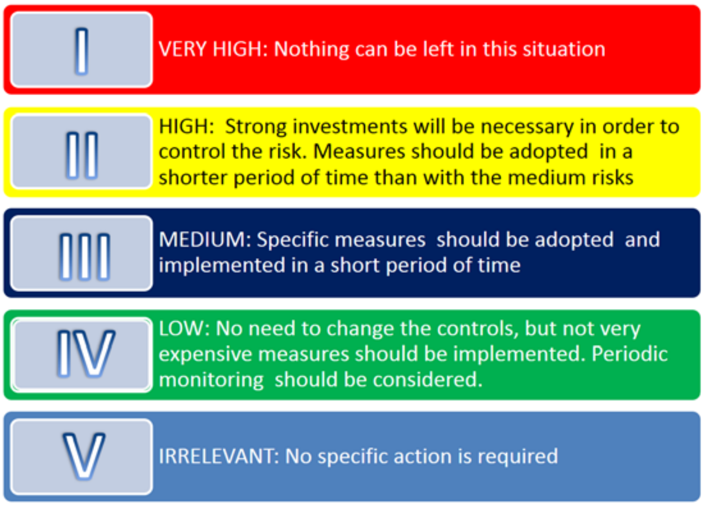


Figure 2-91. Scale of risks.

To rank risks, we need to find first the consequence descriptor that best fits the situation and then to define the probability with which those consequences will occur. The level of risk is then read off from the matrix.

The residual risk will also be determined using the same risk matrix after proposed treatment actions are identified.

REGIONAL INTEGRATION

It was proved not feasible to develop the estimation of treatment failure probabilities and their uncertainty bounds, based on the project's timeline that is specified in Task 4.3, due to the inexistence of available data regarding the risks addressed within the project.

Thus, and in order to consider how proposed risk mitigation strategies which address a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk), it was decided to accomplish this task by an adequate methodology, according to IEC/ISO 31010: 2009, allowing to address how a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk).

In the risk assessment process used for the four main risk components outlined previously, the risk identification stage advocated the use of tree diagrams. These were used both to show the causes and the effects of those hazards in some detail. It was therefore decided to build on from this and use "bowtie diagrams" in order not only to show this cause-consequence relationship in full, but also to demonstrate how those hazards are interrelated and to determine how they could be mitigated further through risk treatment.

The use of Bowtie diagrams has recently emerged as a popular method of assessing and analysing risk associated with major safety hazards (high consequence-low likelihood risks) in many industries including mining. Bowtie diagrams were developed formally by Shell as part of their Tripod package of concepts and tools for the management of health and safety at its operations in the 1990's (Iannacchione et al, 2008).

A Bowtie diagram is a development of a combination of a fault tree on the pre-event side and an event tree on the post-event side that has been flattened and simplified. The primary motivation for its development was to seek assurance that fit for purpose risk controls were consistency in place. Its use has spread between companies and regulators and its application has been extended to consider other business risks, and not just safety.

Detailed risk assessments have been undertaken on the four major components of environmental risk and these have been presented for both Polish and Spanish mines. The risk analysis has been based on the detailed modelling presented in WP2 and an evaluation of the current level of risk determined using an integrated risk matrix.

The Partners responsible for each risk component also developed a generic Bowtie analysis (BTA) for each, not only showing the causes and consequences outlined in the risk assessments, but also undertook to identify the typical "best practice" risk treatment options or control measures that could be considered and used to ensure the associated risk was at an acceptable level.

The risk evaluations in the original assessments were based on the level of risk now at the present time at the specific mine sites which may not have included all of the risk treatments options identified on the Bowtie diagrams.

A BTA for Gas emissions, Surface Deformation, Groundwater and Surface water respectively were prepared. A fifth BTA, that of Flooding was also prepared as it was noted that flooding was an implied cause or consequence in all of the components. Figure 2-92 presents the groundwater contamination Bowtie diagram.

Through analysis of all five BTA's it was noted that all of the risk components were interrelated, either as a cause or consequence of another component with "flooding due to rising groundwater" a contributing cause for all. This interrelationship is shown in Figure 2-93.

As a result a separate BTA for the event of rising groundwater was drawn up (Figure 2-94).

This BTA has no barriers shown but as many of the consequences are top events in the earlier BTA's those barriers would be those preventative controls that appear on the left hand side of them.

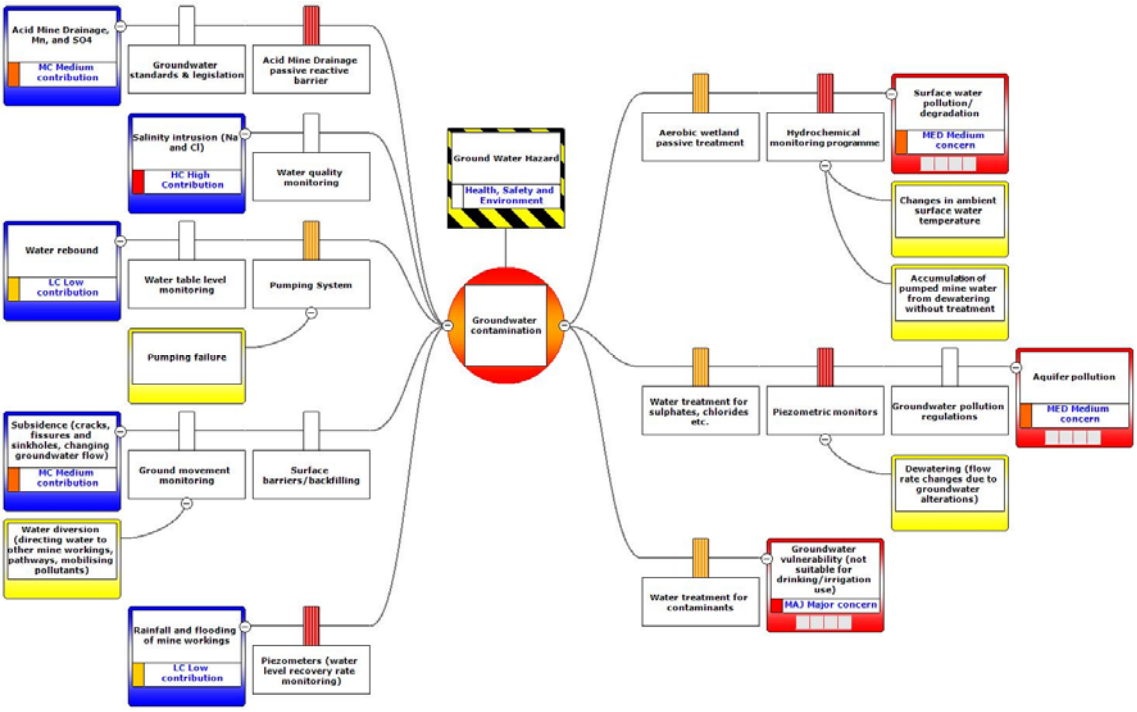


Figure 2-92. Groundwater contamination Bowtie diagram

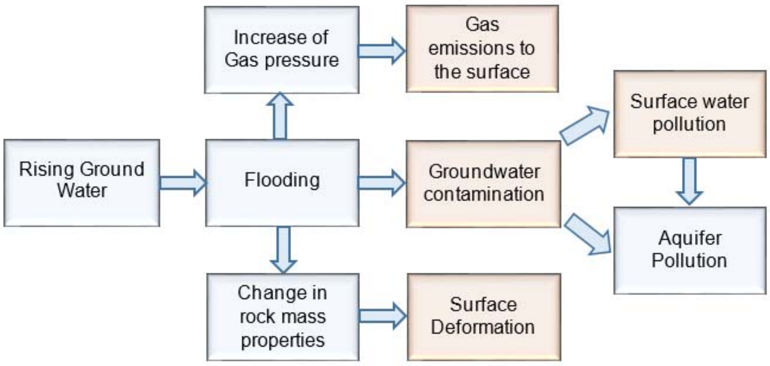


Figure 2-93. Interrelationship of the Risk Components

A common barrier to all of these consequences is pumping (even though this is also one of the causes). These make "pumping" the key current critical control for reducing the associated risk of all these separate components and demonstrates the importance of associated assurance regimes such as inspections, maintenance and pump redundancy.

The concept of critical controls was used to determine what best practice controls shown on the BTA's could be considered as future risk treatment options as they have the potential to reduce risk further. These were identified here and further evaluated in WP4. These options are shown on the BTA's as red tags if they are critical for that particular risk component or orange if they are critical to another of the risk components. A summary is given in Table 2-4.

Thus, BTA's have been created for the five key environmental risk components associated with mine closure. Their causes and consequences were taken from the underlying risk assessments and best practice risk treatment options were identified for each. These BTA's have also shown the relationships between the impacts, and allowed the identification of mitigation alternatives that could reduce the risk further.

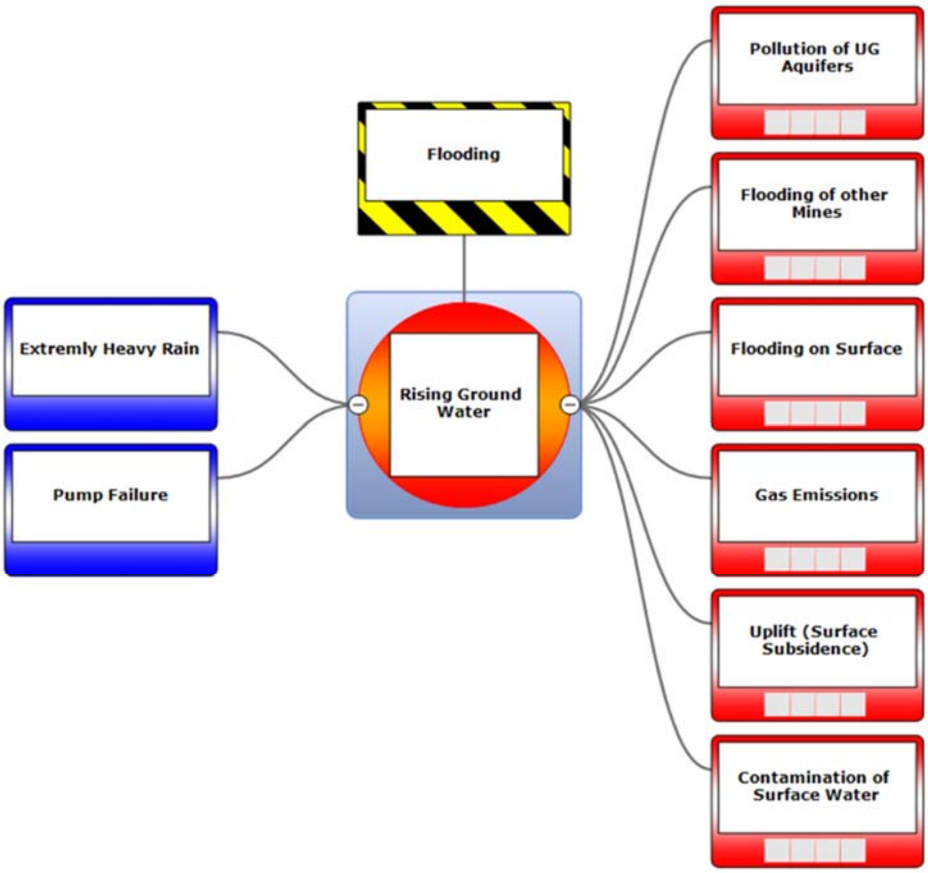


Figure 2-94. Bowtie Diagram of Rising Groundwater

Table 2-4. Critical Controls/Risk Treatment Options

Hazard	Top event (risk components)	Risk Treatment
Gas hazard	Gas Emissions	Gas sensors (inc in the shaft)
		AMM Technology Flares
Ground movement hazard	Surface deformation and mining damage	Geodetic measurements (monitoring)
		Backfilling of old workings
Groundwater hazard	Flooding	Piezometric controls
	Groundwater contamination	AMD passive barriers
		Piezometric control
		Hydrochemical monitoring
Surface water hazard	Surface water contamination	AMD passive treatment

2.3.4 WORK PACKAGE 4: RISK MANAGEMENT AND REMEDIATION MEASURES

T4.1 Forecasting the performance of the selected treatment options in terms of impacts and risks (UNIOVI, all partners)

Impact prediction models devised in WP2 and parameterized in WP3 were used to estimate pollution impacts and risk estimates for the ground movement, groundwater, surface water and for the gaseous emissions for PGG and Hullera del Norte mines studied in the project.

GROUNDWATER RISK MANAGEMENT IN PGG MINES (POLAND)

The selected pollution treatment strategy for groundwater pollution was passive in-situ groundwater remediation using permeable reactive barriers (PRBs). It is considered as a promising technology for effective groundwater remediation. PRB is defined as an in situ permeable treatment zone filled with reactive materials, designed to degrade or immobilize and remediate a contaminant plume under natural hydraulic gradients. The contaminants are removed from the groundwater by geochemical processes taking place in the reactive material of the barrier filling.

PRBs are typically constructed perpendicular to the flow of groundwater. Natural hydraulic gradients transport contaminants through the reactive media within the PRB. When the contaminated water passes through the PRB, contaminants are either immobilized or chemically transformed to a less toxic state by the reactive material contained within the barrier

Suitable materials for use as reactive components in PRBs are elemental iron (zero valent iron), activated carbon, zeolites and peat. The choice of reactive materials and retention mechanisms are dependent on the type of contamination to be treated by the barrier system. Although all of these reactive materials are effective individually, combinations of materials may prove to be optimal for certain contamination situations.

The barrier must be long enough to treat the entire width of the plume (dimension perpendicular to groundwater flow). The problem is to determine the optimal thickness of a PRB, which should provide a residence time appropriate for reducing the concentration of contaminants to the desired effluent concentration.

The residence time is defined as the contact time between the contaminated groundwater and the reactive material required to achieve the treatment goals.

PRBs have a favorable cost/benefit ratio compared to traditional (mostly pump-and-treat) systems used for groundwater remediation. This is true for capital, operation and maintenance costs. The total cost of a PRB system may be at least sixty percent cheaper than the equivalent pump-and-treat system.

For example, the cost for the groundwater treated could range from 4.15 to 6.7 € per cubic meter, depending on the site size and complexity and therefore a PRB system could cost up to 450,000 €, versus the cost for a pump and treat remediation, reaching up to 6.3 M€.

GROUNDWATER RISK MANAGEMENT IN HUNOSA MINES (SPAIN)

Apart from the PRB, in this case, it was decided to develop additional piezometric controls in the area with higher risk of floods, especially south of Tuilla, near Mosquitera 2 in order to fight against floods, as this is the main risk related with underground waters in HUNOSA mines. The reason is that the two piezometers already installed are in a more elevated area, in the quaternary deposits near Mosquitera 1, showing no connection with the Carboniferous aquifer, therefore being perched aquifers not included in the conceptual model.

Also, to install independent powered water level alarm sensors in those piezometers, ideally connected by phone with the person in charge of the pumping system, something that will complement these specific measures.

Finally, with the use of these piezometers, time-series of pumping rates and levels in the mine should be provided with higher sampling frequency (i.e. diary better than monthly), as the estimation of recharge values are of extreme importance to assess the infiltration to the aquifer and relate head variations with rain data.

Also, the installation of at least one weather station (which is relatively cheap) providing daily data of rain and temperature on the study area would provide advantageous information that could be linked to high-frequency series of pumping/levels in the mine.

Referring to the risk analysis of pollution of underground aquifers, the specific measure to adopt is to undertake a hydrochemical laboratory control analysis and head monitoring at water point 1305-3-0011, as it corresponds to a pit with gallery which elevation is below the security level (200 m) so there is a possible flow from the mine, and it is used by industry.

SURFACE WATER RISK MANAGEMENT

Risk associated with iron

To fight against the risk associated with iron, passive treatment systems are a preferable option for treating acid mine drainage for closed mines. They are relatively recent technology that involves benefitting from the advantages of passive treatment systems; namely that they do not require electrical power, any mechanical equipment, no hazardous chemicals, or buildings, nor daily operation and maintenance care, are more natural and aesthetic in their appearance, may support plants and wildlife, and are less expensive.

Among the different options, the settling pond and the aerobic wetland are considered a better approach for net alkaline waters. They are the simplest types of passive treatments and are used to treat mildly acidic or net alkaline waters containing elevated Fe concentrations.

The primary function of the aerobic wetland is to allow aeration of the mine waters flowing among the vegetation, enabling dissolved Fe to oxidize and to increase residence time, where water flow is slowed for Fe oxide products to precipitate. It is also capable of removing manganese Mn concentrations, where applicable. Aerobic wetlands have been shown to be an efficient and cost-effective remediation method, and have been used effectively in different cases, at a cost reaching ~ 23,000 €.

The passive compost system can also be implemented effectively to remove heavy metals found in mine waters, especially Zn, Cu, P. It has been shown to have a very high treatment effectiveness for waters with high salinity, such as the water types here.

Risk associated with sulphates

To fight again the risk associated with sulphates, it was selected the Cost Effective Sulphates Removal (CESR) process, that removes high concentrations of sulphates through addition of hydrated lime ($Ca(OH)2$), which precipitates calcium sulphates.

The CESR process can reduce the sulphates concentration to less than 100 mg/L through use of a proprietary powdered reagent. Addition of the CESR reagent to lime-treated water precipitates sulphates as a nearly insoluble calcium-alumina-sulphates compound known as ettringite. The process produces a net reduction in total dissolved solids (TDS).

Operating costs are typically 1.14 € to 2.28 € per 1,000 liters treated for removal of sulphates, based on reagent consumption. For example, the reagent cost would be approximately 1.14 € per 1,000 littles for removal of 1,500 mg/l of sulphates. This portion of the operating cost is also directly related to the sulphates concentration that needs to be removed.

Risk associated with chlorides

To fight against the risk associated with chlorides, it was selected Vacuum evaporation. It is a clean, safe and a versatile technology, which has a very low management cost. It transforms waste effluent into two streams, one of concentrated waste and another of high quality water. The evaporators work under vacuum, so the boiling temperature of the liquid effluent is lower; thus saving energy and improving efficiency.

The equipment is compact and so the operational monitoring is simple, allowing effluent flows of up to 20 m^3/h to be treated in a single evaporator. As the effluent does not need to be heated at high temperatures, as the water boils at 35-40°C when working under vacuum, the energy requirements are lower.

A mechanical vapor compression system not only greatly reduces energy costs, but also reduces the CO_2 footprint, as it permits the continuous recycling of this energy by compressing the steam. Treatment capacities could range from 1,150-15,000 liters/hour, with a typical operating cost of 2.4-4.8 € per 1,000 liter of condensate.

GROUND MOVEMENT RISK MANAGEMENT

Discontinuous deformations appear on the land surface much less frequently in comparison to continuous deformations. The intensity and speed of their manifestation cause static but violent effects on building objects localized on the area subjected to this influence.

Buildings and other unprotected structures cannot resist efficiently such influences without significant damages, including full destruction of a structure. The most important influence is the change of support conditions under some parts of foundations. It can be related to uneven settlement of a part of building or creation a gap between foundation and subsoil.

Taking the above facts into account, to minimize the existing risk for buildings currently in the zone of potential impact of linear discontinuous deformation, it is necessary to take steps to measure periodically deformation of the land surface. Monitoring of the structures should be understood as measurement of object strains, displacements, tilt (especially long buildings), and regular objects inventory in search of damages (scratches, cracks).

If the newly designed buildings are taken into consideration, it is necessary to introduce information on the possibility of discontinuous deformation occurrence in such area in the land use plan. This information will allow for a partial limitation of the development of this area or the need to protect buildings against discontinuous deformations like grillage foundation, reinforced concrete foundation slab, which provide greater rigidity, stability and resistance.

As was mentioned in fracture, cracks analysis and sinkholes, discontinuous deformations appear on the land surface much less frequently in comparison to continuous deformations. The intensity and speed of their manifestation causes static but violent effects on building objects localized on the area subjected to this influence. Buildings and other unprotected structures cannot resist efficiently such influences without significant damages, including full destruction of a structure.

Taking the above facts into account, to minimize the existing risk for buildings currently in the zone of potential impact of linear discontinuous deformation, it is necessary to take steps to detailed inventory of old shallow excavation and then to backfill them to increase their stability. For this purpose it will be necessary to perform appropriate geophysical surveys, specific drills etc. to determine approximately the shape, volume of voids and its localization.

If the newly designed buildings are taken into consideration, it is necessary to introduce information on the possibility of discontinuous deformation occurrence in such area in the land use plan.

This information will allow for a partial limitation of the development of this area or the need to protect buildings against discontinuous deformations like grillage foundation, reinforced concrete foundation slab.

GAS RISK MANAGEMENT

Due to the possibility of significant concentrations of methane in the Ryszard shaft, it is possible to apply Abandoned Mine Methane (AMM) technology. Depending on the results of measured methane concentrations in the shaft and gas pressure, flares or gas vents or gas engine may be used. Costs for a flare is estimated to be 3,000 € based on different experiences.

In the areas of shallow exploitation, it is necessary to demarcate a zone expanded by 20 metres of the border of shallow exploitation and to make it obligatory to apply gas leak detectors in basements of the buildings located there. Its price is around 25 € per detector.

Finally, to minimise the risk associated with the migration of gases to the mine, Rydułtowy uses the gasometer system functioning at the Rydułtowy mine. This system consists of sensors and a monitoring centre. Because it is a system enforced by mining legislation, there is no need for additional solutions.

This system provides monitoring of gas concentrations and immediate notification of the dispatcher with the permissible concentrations being exceeded. In addition, in workplaces of machines and devices, it ensures that they are stopped and the electricity is switched off in the event of exceeding the set concentrations.

RADON RISK MANAGEMENT

To minimise the existing risk, it is necessary to perform measurements in soil gas in mining and post-mining areas. The results are the basis for the risk classification of building sites. Depending on the class of risk, specific mitigation methods should be performed. The most basic method of reduction of radon gas concentration in the building is increasing ventilation by opening windows more often. In case of the presence of damages of the floor, walls and foundations that open pathways for radon migration, renovation works are needed, sealing of cracks and fissure.

In areas of high radon index (areas where elevated radon concentrations are measured in soil gas), it is recommended to use specialized building foils. So-called "radon blocker foil" limits the penetration of moisture and gases (including radon) into the building. Sometimes it is necessary to build an additional barrier separating the building from the ground.

In case of very high radon concentration in dwellings, it is necessary to install fans and pumps for removing radon from inside buildings.

T4.2 Cost analysis of the pollution treatment options (GIG, UNIOVI,** all partners**)

This task focused on the cost analysis of the selected pollution treatment options for each of the selected PGG and Hullera del Norte mines studied in the project, presenting a detailed description of the different investment and costs.

COST ANALYSIS AND FINANCIAL PROVISIONS FOR PGG MINES

In the first place, for groundwater risk treatment the option that should be installed is a passive in-situ groundwater remediation using permeable reactive barriers (PRBs). Although it is quite a big investment, 450,000 €, it has no maintenance costs on the other hand.

Second, regarding the surface water risk treatment costs, only one pollution treatment option should be installed: aerobic wetlands. The aerobic wetlands will need a yearly maintenance during five years. The mean NPV obtained was -242,896 €. The problem in this case was that although several discharges of water are within the limits imposed by the government to the mine, the concentrations of sulphates and chlorides are so high that it is not feasible from the economic point of view to develop treatments in order to achieve the international standards.

In third place, regarding the ground movement risk treatment costs, only a yearly geodetic campaign should be developed during seven years. The mean NPV obtained was -331,868 €.

Finally, regarding the gas risk treatment costs, gas detectors and methane and radon revisions that will be revised on a yearly basis were the only treatment considered over a period of 10 years. The mean NPV obtained was -32,614 €.

Taking all of them in account and calculating the Net Present Value (NPV), in order to determine the financial provisions required for closure and post-closure regarding groundwater risks, the result was (in fact cost present value, as there are no positive cash flows):

NPV = - 1.060.997 €

The distribution of the investments can be clearly observed in Figure 2-95, with the PRB plant in the first place and the aerobic wetlands in second place. Thus, the investments needed to remediate the groundwater pollution risk are the most expensive of all.

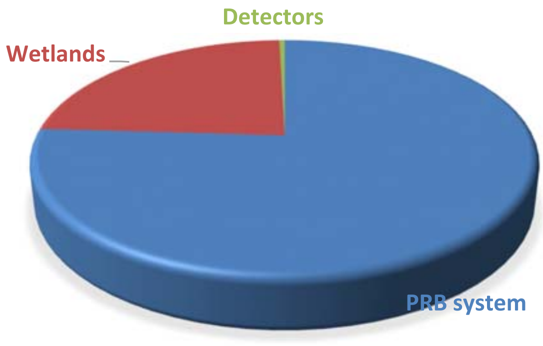


Figure 2-95. Distribution of investments

Addressing now the cash-flows, Figure 2-96 presents the different cash-flows during the 10 years considered.

Figure 2-97 presents a spider graph with the PRB investment as the one to which the variable is more sensitive, followed by the geodetic campaign.

Finally, developing the Monte Carlo analysis, the NPV is presented in Figure 2-98. Thus, the final NPV will have a mean of -1,057,318 €, a maximum of -995,134 €, a minimum of -1,164,160 € and a standard deviation of 22,284 €.

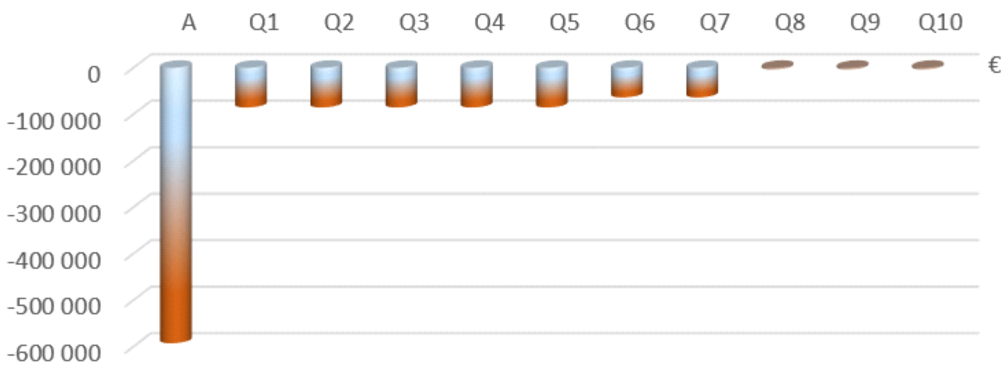


Figure 2-96. Cash flows of the treatment strategies

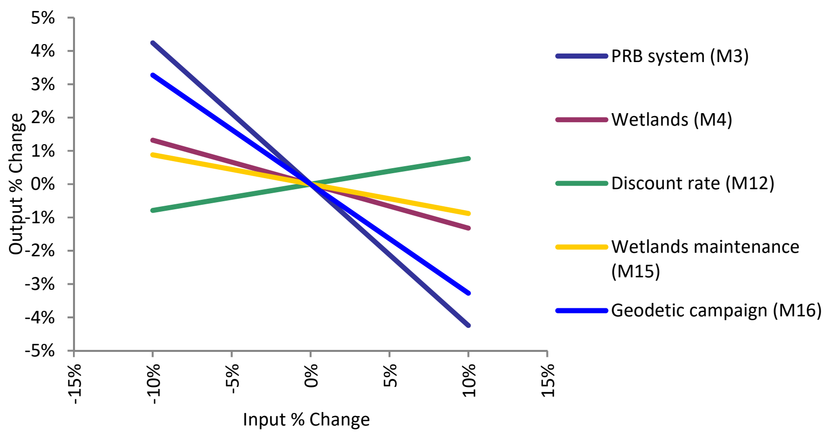


Figure 2-97. Spider graph for the main variables to which NPV is more sensitive

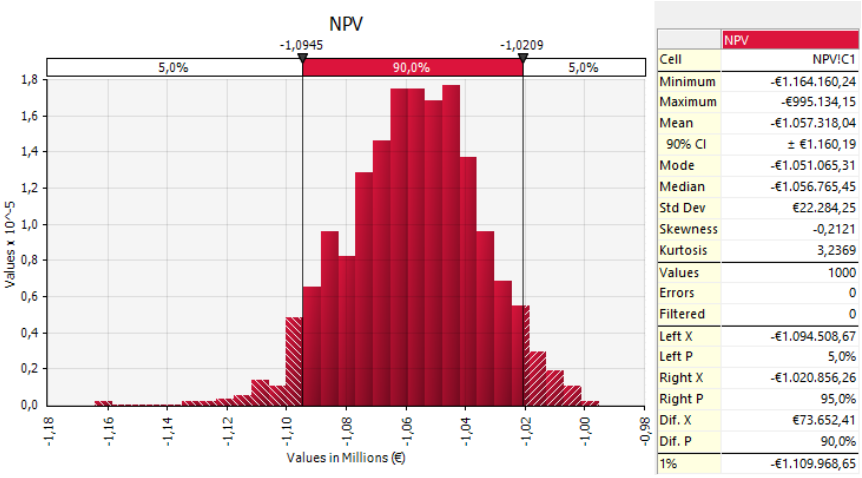


Figure 2-98. Monte Carlo analysis or the NPV of the cost analysis of the selected treatment options

COST ANALYSIS AND FINANCIAL PROVISIONS FOR HUNOSA MINES

In the first place, groundwater risk treatment costs were analysed. The different treatment options that should be installed were additional piezometric controls, independent powered water level alarm sensors ideally connected by phone and a wireless weather station.

The biggest investment corresponds to the installation of the piezometers. On the other hand, it was considered the yearly line maintenance for the water level alarm sensors, the yearly monitoring of piezometers and the weather station, as well as the yearly cost of water analysis.

The NPV obtained was -67,175 €, being the variable to which the NPV has more sensitivity the monitoring of the piezometers, as they last for 20 years.

Secondly, surface water risk treatment costs were analysed. The different pollution treatment options that should be installed were aerobic wetlands and a Cost effective Sulphate Removal (CSR) plant.

The aerobic wetlands will need a yearly maintenance during a five years period, the same period in which CSR will be operating incurring in operation costs.

The NPV obtained was -2,202,437 €, being the variable to which the NPV has more sensitivity the yearly operating cost of the CSR plant.

In third place, the ground movement risk treatment costs were considered. Only a yearly geodetic campaign should be developed during 7 years. The NPV obtained was -260,387 €.

Finally, the gas risk treatment costs were analysed. Installing gas detectors that will be revised on a yearly basis was the only treatment considered.

The NPV obtained was -37,760 €, having the NPV almost the same sensitivity respect these two variables. The revision was considered as necessary over a period of 10 years.

Taking in account all of them and calculating the Net Present Value (in fact cost present value, as there are no positive cash flows) in order to determine the financial provisions required for closure and post-closure regarding groundwater risks, the result was:

NPV = -2.564,408 €

The distribution of the investments can be clearly observed in Figure 2-99, with the CSR plant in the first place and the aerobic wetlands in second place. Thus, the investments needed to mitigate the surface water (environmental) risk are the most expensive of all.

Addressing the cash flows, Figure 2-100 presents the different cash-flows during the 20 years considered.

Although quite logical, Figure 2-101 presents a spider graph with the CSR operating costs being the ones to which the variable is more sensitive.

Running the Monte Carlo analysis, the NPV is presented in Figure 2-102. Thus, the final NPV will have a mean of -2,664,337 €, a maximum of -2,552,024 €, a minimum of -3,147,186 € and a standard deviation of 64,789 €.

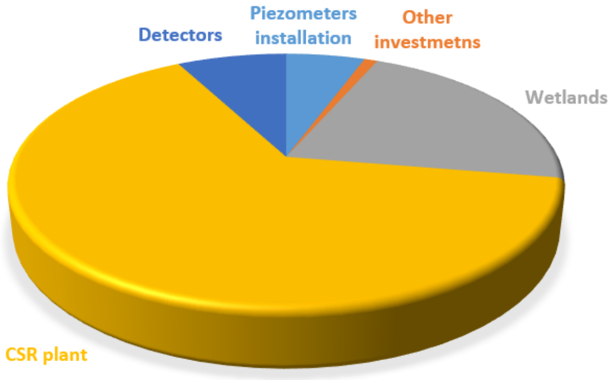


Figure 2-99. Distribution of investments

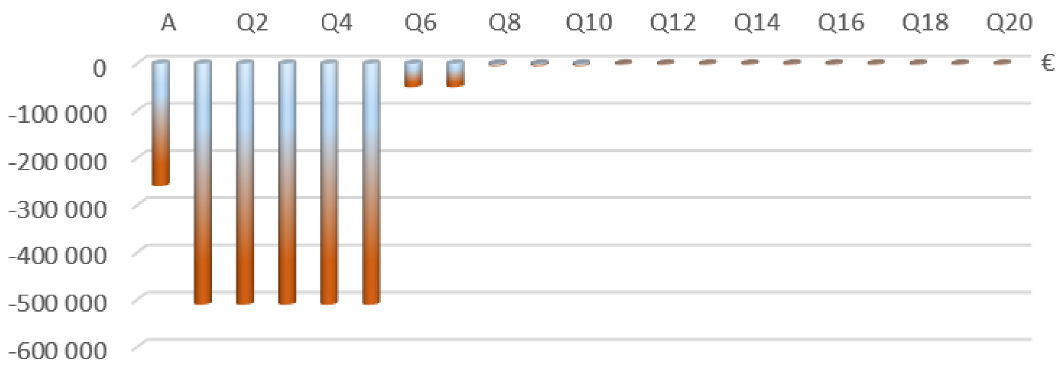


Figure 2-100. Cash flows of the treatment strategies

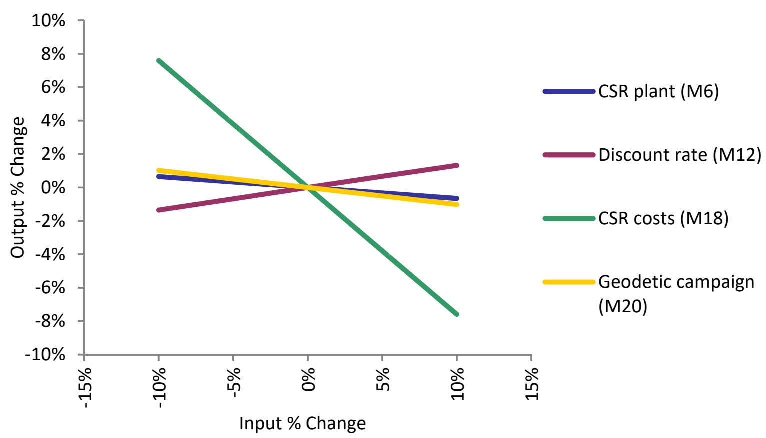


Figure 2-101. Spider graph for the main variables to which NPV is more sensitive

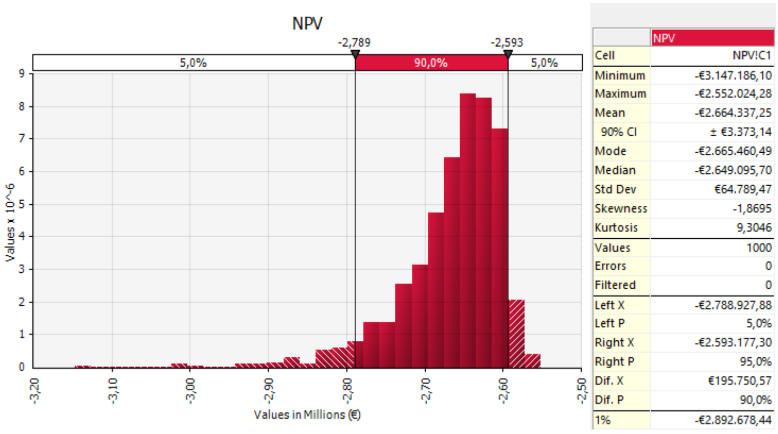


Figure 2-102. Monte Carlo analysis or the NPV of the cost analysis of the selected treatment options

T4.3 Estimating treatment failure probabilities and their uncertainty bounds, based on the project's timeline (GIG, UNIOVI,** all partners**)

It was proved unviable to be developed via Probabilistic Risk Assessment (PRA), due to the inexistence of available data regarding the risks addressed within the project. Thus, and according to IEC/ISO 31010: 2009, an adequate methodology to address how a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk), was the Bowtie analysis, so this was the methodology used instead of Probabilistic Risk Assessment.

All results from Task 4.3 (the applied Bowtie methodology) were used for developing Task 3.5 Regional integration of different risk components. To avoid repetition, they are only presented under the Task 3.5.

2.3.5 Work Package 5: Dissemination

T5.1 Produce a best practice guideline for the prediction of environmental impacts and the management of risk during coal mine closure and post-closure (EXETER,** all partners**)

An "Environmental impact prediction and risk management methodology for coal mine closure and post-closure" covering surface deformation, groundwater, surface water and gaseous emissions, including radon, was delivered and documented as a recommendation for good practices.

T5.2 Workshop on Environmental Impact Prediction and Risk Management for Coal Mine Closures (GIG,** all partners**)

A Mining Conference took place from the 6th till the 7th of November, 2019, at SPA Hotel Jawor, in Jaworze. On the 6th of November, a special session for the MERIDA project was developed.

T5.3 Scientific publications, conferences and a Special Issue in the Journal of Sustainable Mining (GIG,** all Partners**)

Five publications about the project were delivered in very high impact journals: Journal of Cleaner Production, International Journal of Rock Mechanics and Mining Sciences, Journal of Hydrology, Science of the Total Environment and International Journal of Coal Geology. Moreover, other eleven publications or congress presentations were delivered.

2.4 CONCLUSIONS

A full description of the two European mining sites was achieved. All the information needed to develop the project related with Rydułtowy-Anna Mining Complex as well as Mosquitera and Pumarabule Mines were gathered and presented in the way to develop further the project. It can be stated that both mines in context of geological and mining condition are somehow representative for the mining basins where they are located. All the information concerning description and digital production, geological and environmental data was uploaded to the intranet and available to all the project partners during the development of the project.

Apart from these descriptions, it was necessary to recollect additional information to serve as proxy input data in the modelling process:

a) Degassing properties of coal samples (i.e. CH_4 emissions) under water pressures were established. The influence of water pressure that will evolve during and after mine flooding on CH_4 emissions was determined. Results for experiments on dry samples help understanding methane-degassing process from dry coal before mine flooding. Results indicate that increasing hydrostatic pressure seems to slow the desorption kinetics; also that with increasing pressure on the water layer, the pressure increase in the air cushion decreases, which means that the methane emission is inhibited. For the flooded sample, this effect is eliminated due to the formation of a barrier for methane, which prevents resorption on the coal. Finally, an in order to effectively inhibit the emission of methane from coal, it is necessary to apply pressure to the water layer twice as high as the pressure of methane injection.
b) Soil gas flux measurements in Spain and Poland were made, allowing to develop a reference guide on soil gas monitoring in coal mining regions, giving guidance, warnings and recommendations. Drivers of mine gas migration to the surface were described and threshold values were presented with usual values as well as anomaly thresholds according to previous Ineris studies.
c) Hydrogeology was evaluated and surface water related environmental impacts of mine closure and post-closure were assessed based on the discharged water quality measurements. Also, an imputation method to supplement the missing and below detection limit values for the relevant parameters was implemented, in order to preserve important information held in the monitored data for the geochemical speciation analysis and to obtain a valid statistical interference.
d) A report on historical data related with environmental incidents and risks following closure in European coal mines, giving a very good spectrum of problems related to abandonment of the mines and a possibility to learn from the experience of the partners that are now after the process of liquidation and dealing with its consequences.
e) A comprehensive report and analysis of coal mine closure risk criteria for ground movement, surface and groundwater pollution, sediment and soil pollution and air pollution (including GHG and radon) were developed, considering current environmental, ecological and human health regulatory requirements, and compared to historical and more recent requirements in relation to regional settings, climatic and environmental conditions. This report and analysis allow to set the benchmark of acceptable thresholds against which risk evaluation will be carried out.

The second step within the project was to develop site specific issue based models to evaluate quantitatively the environmental impacts during coal mine closure and post-closure periods in different European coal mining regions:

a) A suitable and validated model to proper describe the behaviour of rock mass in a region of flooded coal mines was implemented, including not only the behaviour of flooded fractured rock mass but also representing the possible surface deformation. The model was developed using the mediums density change method as after a number of analysis using alternative methods (pore pressure change method and hydrostatic pressure change method) it achieved the best calculations. The results of the model allowed obtaining the distribution of deformation indicators and stresses on the ground surface. In addition, distribution of these indicators in the rock mass was achieved.
b) Suitable and validated models to proper describe groundwater flow and solute transport during the water rebound process, according to the specificity of the different sites, were implemented. In the case of Rydułtowy-Anna Mining Complex, a groundwater chemical flow model encompassing multiple regions to estimate the environmental impact associated with water rebound, developed by means of FEFLOW. In the case of Mosquitera and Pumarabule Mines, a groundwater flow and solute transport model in flooded underground coal mines by means of COMSOL Multiphysics. The results of the models allowed obtaining water and pollution related variables of interest to assess the environmental risks associated with mine closure.
c) Suitable and validated models to evaluate quantitatively the surface water environmental impacts during coal mine closure and post-closure periods were implemented. The aqueous water geochemistry software WHAM7 and bioavailability M-BAT tool were used to model the water quality and pollutant bioavailability. The discharged water quality (or surface water quality) was modeled with the Windermere Humic Aqueous Model to predict reliably metal binding to natural Dissolved Organic Matter, as it calculates effectively the interactions of protons and metals with the humic substances (fulvic and humic acids). The results of the models provided the component complex concentrations in the aqueous phase, the free ion activity and the fraction of each component for each of the colloidal phases. In addition, the bioavailability tool assessed the potential toxic effect of the studied free metal ions.

d) Suitable and validated models to assess the greenhouse gas emissions from closed mines with or without flooding to the surface were implemented. In the first place, a model to calculate the amount of methane emission rates from goafs based on the methane-bearing capacity of the mined seams and the average methane emission throughout the life of the longwalls. Second, a model to identify methane flow paths in a closed mine and to determine methane concentrations in individual areas of the mine by means of Ventgraph software. Third, a model for radon exhalation by means of a Ventgraph Radon module. Results determined the places of possible gas outflow to the surface, as well as maps of the areas where risk of gas outflow possibly exists.

The third step was to develop an ArcGIS database with the modelling results integrated in the database and the web-based visualisation environment, allowing the joint interpretation of the different environmental impacts in relation to their spatial distribution and the sensitive receptors. The database was provided with an analytic tool in order to allow the user analyzing interactions among any variables by means of measures, cross-sections and heatmaps. In addition, the database was also provided with a tool allowing user-friendly comparison of different water chemical parameters over time. The database can be freely accessed at: https://safeguard.dmt.de/merida/?lang=en.

In fourth place, reports on the risk identification, risk analysis, risk evaluation and proposed treatment of areas exposed to ground movement risk, groundwater risk, surface water risk and gaseous emissions risk at the selected PGG and HUNOSA mines were developed.

All the reports were made using the same methodology that follows the IEC/ISO 31010 (2009): cause-and-effect analysis as risk identification method, and consequence/probability matrix as risk analysis method with a scale of consequences developed according to the economic impact of losses as defined by mining insurance companies.

In fifth place, a report on the streamlined integrated risk mitigation options at the selected PGG and HUNOSA mines, considering how proposed risk mitigation strategies which address a given risk component may affect other individual risk components positively (reducing the individual risk) or adversely (increasing the individual risk), was developed. Bowtie analyses were made for the different environmental risks under study, noting that all of the risk components were interrelated, either as a cause or consequence of another component with "flooding due to rising groundwater" a contributing cause for all. As a result, a separate Bowtie analysis for the event of rising groundwater was drawn up, showing the relationships between the impacts, and allowing to identify mitigation alternatives that could reduce the risk further.

In sixth place, reports on the forecasted environmental performance of the selected treatment options in terms of impacts and risks, at the selected PGG and HUNOSA mines were developed. These reports will allow to elaborate final closure assessment plans by means of selecting the most feasible treatment alternatives for the different environmental impacts together with the transitional monitoring that could guarantee a hazard level in compliance with land re-use and use of natural resources.

Finally, and based on the previous reports, cost analysis and financial provisions required for closure and post-closure for the selected PGG and Hullera del Norte mines wee developed. A detailed description of the different investment and costs needed for the different pollution treatments was presented. Taking all of them into account, Net Present Values were calculated, in order to determine the financial provisions required for closure and post-closure stages. Then, sensitive analysis of the calculations was developed, followed by uncertainty analysis. Taking also into consideration that some hazards were not feasible to be treated, financial provisions that will allow the government to develop specific policies addressing the most impacted areas, were estimated. Finally, the financial provision that each company should provide in order to face all the costs to fight the different environmental risk was estimated.

The cost analysis and financial provisions required for closure and post-closure for the selected PGG mines were estimated in a maximum of 1,164,160 €, so a conservative financial provision of 1,200,000 € was considered. However, this figure was obtained without considering the treatment of the high impacts that the different surface water discharges will produce regarding the amount of sulphates and chlorides, as it was not economically feasible.

Within the risk analysis the consequence descriptors that best fit the different situations were developed according to an economic scale of losses that is used by the insurance companies within the mining sector when defining the different kind of sinisters. Thus, these quantities can be used in order to estimate a financial provision that may allow the government to develop specific policies addressing the most impacted areas.

At discharge point PS1 both sulphates and chlorides exceed quite a lot the quality standards, so these can be compared with the biggest of major impacts, that is, 600,000 € in each case. Thus, a provision of 1,200,000 € should compensate in some way the impact caused.

According to this, the financial provision that the company should provide in order to face all the costs to fight the different environmental risk could be estimated in around 2,400,000 €. Of course, it does not consider the costs related with water pumping or with shafts sealing.

On the other hand, the cost analysis and financial provisions required for closure and post-closure for the selected Hulleras del Norte mines were estimated in a maximum of 3,147,186 €. According to this, the financial provision that the company should provide in order to face all the costs to fight the different environmental risk could be estimated in approximately 3,200,000 €. Of course, this amount does not consider the cost related with water pumping or with the sealing of the shafts.

As a conclusion, costs related with water pollution treatment are the biggest of all, being approximately the 80% of total costs. Thus, water can be considered as the critical environmental risk when addressing the closure of a coal mine both in the Silesian coal basin and in the Asturian coal basin.

2.5 EXPLOITATION AND IMPACT OF THE RESULTS

Most of the work developed within the project has very good potential for future exploitation in Europe, mainly within the Coal Regions in Transition Platform:

1) Degassing properties of coal samples (i.e. CH_4 emissions) under water pressures.
2) Reference guide on soil gas monitoring in coal mining regions, giving guidance, warnings and recommendations.
3) Report on historical data related with environmental incidents and risks following closure in European coal mines.
4) Report and analysis of coal mine closure risk criteria for ground movement, surface and groundwater pollution, sediment and soil pollution and air pollution (including GHG and radon).
5) Model to describe the behavior of rock mass in a region of flooded coal mines.
6) Models to describe groundwater flow and solute transport during the water rebound process.
7) Models to evaluate quantitatively the surface water environmental impacts.
8) Models to assess the greenhouse gas emissions from closed mines with or without flooding to the surface.
9) Risk assessment methodology.
10) Financial provisions calculation.

Apart from that, first, an "Environmental impact prediction and risk management methodology for coal mine closure and post-closure" was delivered, conceived as best practice guidelines covering ground movement, groundwater and surface water and gaseous emissions. It was documented as a recommendation for good practices.

The aim being to provide a tool for coal mining companies and regulators that can be used to deal with the major environmental risks during underground coal mine closure and post-closure periods in a structured and systematic manner, both qualitatively and quantitatively.

Second, a workshop on environmental impact prediction and risk management for coal closure and post closure was celebrated, making it coincident with an important mining congress organized by GIG on the 6th-7th November 2019, in the SPA Hotel Jawor, Jaworze.

The methodology and results generated during the project were presented in English and in Polish during the 6th of November, within a special session for the MERIDA project. Thirteen presentations about the project were delivered, covering all the main aspects. In Table 2-5 there is a relation of the different presentation given about the MERIDA project.

Table 2-5. Presentations given at the mining Congress

No.	Title of the presentation	Speaker
1	Introduction to the project: Towards sustainability in underground coal mine closure contexts	Alicja Krzemień

2	A review environmental incidents and risks following closure in European coal mines	Patrick Foster
3	Information required addressing environmental management during coal mine closures	Juan J. Álvarez Fdez.
4	Groundwater model and risk assessment at Mosquitera and Pumarabule Mines (HUNOSA, Spain)	Pedro Riesgo Fdez.
5	Surface water quality and ecological risk assessment - Assessing heavy metal impacts post-mining through chemical equilibrium and toxicity modelling at Rydułtowy-Anna Mining Complex & Mosquitera and Pumarabule Mines	Maria Lathouri
6	Ground movement model and risk assessment at Anna and Candin mines	Mateusz Dudek
	Gaseous emission model and risk assessment (Poland)	
7	Forecast of methane emission from closed underground coal mines exploited by longwall mining	Eugeniusz Krause
8	Modelling of gas emission from closed underground coal mines exploited by longwall mining	Jerzy Krawczyk
9	Gas risk assessment: Identification of possible gas emission zones to the surface in Anna mine	Aurélien Gouzy
10	Radon migration in the area around the coal mine during closing process	Małgorzata Wysocka
11	Online data management and visualization tool to demonstrate spatial integration of different risk components in the framework of MERDA project	Jörn Wagner
12	Cost analysis of pollution treatment options in coal mine closures	Pedro Riesgo Fdez.
13	Best Practice Guidelines on underground coal mine closures	Patrick Foster

Third, five publications about the project were delivered in very high impact journals. Moreover, other eleven publications or congress presentations were delivered:

PAPERS IN JOURNALS WITH IMPACT FACTOR

RIESGO FERNÁNDEZ, P., RODRÍGUEZ GRANDA, G., KRZEMIEŃ, A., GARCÍA CORTÉS, S., FIDALGO VALVERDE, G. (2020). Subsidence versus natural landslides when dealing with property damage liabilities in underground coal mines. International Journal of Rock Mechanics and Mining Sciences, 126(November 2019). https://doi.org/10.1016/j.ijrmms.2019.104175

GONZÁLEZ-QUIRÓS, A., FERNÁNDEZ-ÁLVAREZ, J. P. (2019). Conceptualization and finite element groundwater flow modelling of a flooded underground mine reservoir in the Asturian Coal Basin, Spain. Journal of Hydrology, 578(August), 124036. https://doi.org/10.1016/j.jhydrol.2019.124036

SKUBACZ, K., WYSOCKA, M., MICHALIK, B., DZIURZYŃSKI, W., KRACH, A., KRAWCZYK, J., PAŁKA, T. (2019). Modelling of radon hazards in underground mine workings. Science of The Total Environment, 695, 133853. https://doi.org/10.1016/j.scitotenv.2019.133853

WYSOCKA, M., SKUBACZ, K., CHMIELEWSKA, I., URBAN, P., BONCZYK, M. (2019). Radon migration in the area around the coal mine during closing process. International Journal of Coal Geology, 212(Aug.), 103253. https://doi.org/10.1016/j.coal.2019.103253

KRZEMIEŃ, A.; SUÁREZ SÁNCHEZ, A.; RIESGO FERNÁNDEZ, P.; ZIMMERMANN K. & GONZÁLEZ COTO, F. (2016). Towards sustainability in underground coal mines closure contexts: A methodology proposal for environmental risk management. Journal of Cleaner Production 139, 1044-1056. https://doi.org/10.1016/j.jclepro.2016.08.149

OTHER PUBLICATIONS

DZIURZYŃSKI W., GRZYWACZ M., KRAWCZYK J. (2019) Analysis of Ventilation System and Assessment of Hazards in the Process of Progressing Liquidation of Workings in Mine 'S'. In: Widzyk-Capehart E., Hekmat A., Singhal R. (eds) Proceedings of the 18th Symposium on Environmental Issues and Waste Management in Energy and Mineral Production. SWEMP 2018. Springer, Cham, https://doi.org/10.1007/978-3-319-99903-6_20

DZIURZYŃSKI W., KRACH A., KRAWCZYK J. PAŁKA T. (2019) A method for estimation of the radioactive radon decay products concentration in the ventilation networks of underground mines, In: Chang, Xintan (Ed.) Proceedings of the 11th International Mine Ventilation Congress Addenum, pp 165-173.

KRAUSE, E., KARBOWNIK, M. (2019). Tests of methane desorption and emission from samples of hard coal in the context of mine closures through flooding. Journal of Sustainable Mining, 18(3), 127–133. https://doi.org/10.1016/j.jsm.2019.03.005

DUDA, A., KRZEMIEŃ, A. (2018). Forecast of methane emission from closed underground coal mines exploited by longwall mining – A case study of Anna coal mine. Journal of Sustainable Mining 17, 4, 184-194. https://doi.org/10.1016/j.jsm.2018.06.004

DVOŘÁČEK, J., SOUSEDÍKOVÁ, R., KUDELOVÁ, Z., VRÁTNÝ, T. (2018). Mineral Commodity Market Trends. Proceedings of International Conference "The Present and Future of the Mining and Geology", 04 – 05 October 2018, Demänovská dolina, Slovak Republic. Slovakian Mining Society, ISBN 978-80-89883-05-9, pp. 7 – 15.

DZIURZYŃSKI W., KRAWCZYK J., PAŁKA T., KRACH A.,2018: Abandonment of the Anna coal mine ventilation network – a numerical simulation, (in Polish), Prace Instytutu Mechaniki Górotworu PAN, vol.20 no.3s.189-196.

KRZEMIEŃ, A., KOTERAS, A. (2018). Environmental risk criteria for effective risk management in underground coal mine closure contexts. The 25th World Mining Congress 2018. Proceedings. Safety and Health in Mining. Astana, 2018.

DRZEWIECKI, J., FREJOWSKI, A. (2017). Opracowanie fizycznego modelu górotworu dla potrzeb modelowania numerycznego procesu zatapiania kopalń. XXIV Międzynarodowa konferencja naukowo-techniczna Górnicze Zagrożenia Naturalne 2017. Ustroń. 4-6.10.2017

DVOŘÁČEK, J., SOUSEDÍKOVÁ, R., KUDELOVÁ, Z., MATUŠKOVÁ, S. (2017). The issue of sustainable industrial growth as regards mineral resources. In: Lenka Štofová, a Petra Szaryszová, ed. New Trends in Process Control and Production Management: Proceedings of the International Conference on Marketing Management, Trade, Financial and Social Aspects of Business (MTS 2017), May 18-20, 2017, Košice, Slovak Republic and Tarnobrzeg, Poland. London: CRC Press/ Balkema, 2018, s. 101-104. ISBN 978-1-138-05885-9

TAJDUŚ, K., SROKA, A., MISA, R., DUDEK, M. (2017). Przykłady zagrożeń powierzchni terenu deformacjami nieciągłymi typu powierzchniowego ujawniające się nad zlikwidowanymi podziemnymi wyrobiskami górniczymi. Prace Instytutu Mechaniki Górotworu PAN. Tom 19, nr 3, wrzesień 2017, s. 3-10.

TAJDUŚ, K., SROKA, A., MISA, R., DUDEK, M. (2017). Zagrożenia powierzchni terenu deformacjami ciągłymi i nieciągłymi aktywującymi się podczas zatapiania podziemnych kopalń. Prace Instytutu Mechaniki Górotworu PAN. Tom 19, nr 4, grudzień 2017, s. 9-20.

Concluding, the degassing properties of coal samples under water pressures, the reference guide on soil gas monitoring in coal mining regions, the imputation method to supplement the missing and below detection limit values, and the report and analysis of coal mine closure risk criteria, could be applied by coal mining companies focusing their closure of post-closure process.

The same happens with the methodologies that were used for developing the models on ground movement, groundwater, surface water and gases, although, in both cases, the mining companies should involve experts in these different fields.

Finally, the risk assessment methodology as well as the financial provisions calculations that were developed, cover a practical gap in mining knowledge, clearly indicating the steps that should be followed in order to fully address the management of environmental risks during and after mine closure.

LIST OF FIGURES

Figure 2-1. Methane release from dry coal under different free gas phase pressures..................16

Figure 2-2. Care device: principle of gas accumulation in the chamber to measure the flux, and CO_2 flux measurement in point D5 (maximum value of summer campaign) 16

Figure 2-3. Mine gas migration paths towards the surface 18

Figure 2-4. Representation of the threshold values of CO_2 flux from soils (Pokryszka, 2017)........19

Figure 2-5. Generated model for Anna mine, with flooding zones marked in red.........................26

Figure 2-6. Distribution of the ground surface deformation and rock mass deformation (mm)......27

Figure 2-7. Vertical view of the changes in vertical displacements (mm) on the ground surface and in the rock mass for post-mining state (a) and after flooding of goafs (b)...................................27

Figure 2-8: A map of seams exploited in the Candín Mine belonging to HUNOSA 28

Figure 2-9: A numerical model for region A of the Candín Mine: a) the entire model with an indicated extraction zone, b) a parcel undergoing extraction, along with the cave-in zone.........................29

Figure 2-10: Successive maps of vertical displacements (mm) for states before and after flooding for: a) region B, b) region C, c) region D 30

Figure 2-11. Distribution of the ground surface deformation and rock mass deformation (mm) 30

Figure 2-12: a) Scheme of main drainage system from the Chrobry I shaft ((Anna Colliery, region R) to the Leon IV shaft (Rydultowy Colliery), and b) the conceptual groundwater flow model for the mining area of interest, showing the shafts at Anna-Rydultowy mining complex.........................31

Figure 2-13: a) A 3D profile of the model and horizons, and b) the extended domain for the 3D ground water model superimposed on the mine layout map..32

Figure 2-14: 10-layer 3D groundwater implemented in FEFLOW 7.0. a) Hydraulic conductivity Kxx (m/d), and b) specific yield (frac.)..32

Figure 2-15: Snap shots of mined out longwall panels in individual seams................................33

Figure 2-16. Hydraulic head distribution at three different levels 34

Figure 2-17. (a) Schematic of regional watersheds and the location of Anna and Rydultowy mine shafts, and (b) model domain for groundwater and contaminant transport modelling, with the Rydultowy mine shafts considered as potential sources for surface water contamination 34

Figure 2-18. Extension of the conceptual model 35

Figure 2-19. Conceptual scheme showing main flow directions assumed in the model.................35

Figure 2-20. Schematic representation of some elements of the mine to be included in the numerical model 36

Figure 2-21. Plain view showing main processes taking place and to be modelled.......................36

Figure 2-22. Example results of the synthetic model for groundwater in Spain 37

Figure 2-23. Construction of the model volume by clipping of boundaries for Mosquitera and Pumarabule Mines 37

Figure 2-24: Example results of hydraulic head distribution at -50 m.a.s.l. 38

Figure 2-25: 3D view of the model showing Reynolds' number in the mine conduits. Turbulent flow regime in the shafts, main roadways near the shaft and mine communications 38

Figure 2-26: Maximum calculated flooding potential zone fro Spain 39

Figure 2-27. Evolution of iron concentration after water rebound...40

Figure 2-28: Concentration of iron content (µg/L) in the mine voids 1 (upper left), 2 (upper right), 3 (bottom left), and 4 years (bottom right) after the flooding has finalized..................................40

Figure 2-29. The water sampling locations at a) Mosquitera mine (Spain), and b) Anna mine (Poland) 42

Figure 2-30. Copper speciation in the discharge water locations of the Mosquitera and Pumarabule Mines 43

Figure 2-31. Zinc speciation in the discharge water locations of the Rydułtowy-Anna Mining Complex 43

Figure 2-32. Model of methane emission from goafs (Krause & Pokryszka, 2013) 44

Figure 2-33. Conceptual scheme of the Ineris mathematical model of firedamp reservoir 45

Figure 2-34: Connecting mine ventilation networks with the grid of goaf branches 45

Figure 2-35: An example of methane distribution calculation in a system of connected goaf and mine ventilation network 46

Figure 2-36. Forecasted methane emission into goafs of Anna coal mine seams, 2017-2032........46

Figure 2-37. Identified places of methane emission from goafs and percentage of flooding 47

Figure 2-38. Distribution of methane concentration in the ventilation network and goaf for the initial state of the abandonment- fan at the shaft Ryszard II is operating (July 2017) 48

Figure 2-39. Changes of the inflow of the air-methane mixture from the Ryszard shaft to the atmosphere during the abandonment of the ventilation system of the Anna mine 48

Figure 2-40. Areas of Anna mine area with a risk of gas outflow...48

Figure 2-41. Spatial diagram of the area of longwall R-15, rate of flow = 1461 m^3/min, distribution of radon concentration in headings and gob 51

Figure 2-42. Distribution of radon concentration in headings and gob 51

Figure 2-43. Spatial diagram of the Anna mine, fan duct WOK-D3–Ryszard II shaft, air outlet from mine 52

Figure 2-44. Mining drift Jedlownik 53

Figure 2-45. Ground movements when flooding up to -800m 53

Figure 2-46. Chlorides plume (red) predicted during the first year and superimposed over the footprint of the surface aquifer 54

Figure 2-47. 3D representation of Anna Mine model..54

Figure 2-48. Surface water sampling locations of the measurement campaigns around Rydułtowy-Anna mining complex 55

Figure 2-49. Flood probability in Mosquitera and Pumarabule Mines...55

Figure 2-50. Combination of flood probability and ground movement damages 56

Figure 2-51. Combination of hydrovelocity heat map and flood probability................................56

Figure 2-52. Cross-section of flood probability 56

Figure 2-53. Diagram of the ground movement hazards related with mine flooding 57

Figure 2-54. Uplift and subsidence of the surface (Pöttgens, 1985)...58

Figure 2-55. Predicted uplift for Anna mine obtained using Sroka's method 59

Figure 2-56. Forecasted uplift caused by mine flooding 59

Figure 2-57. Risk evaluation for Stage I 60

Figure 2-58. Risk evaluation for Stages II and III 60

Figure 2-59. Part of a region disturbed by geotechnical fault. The red color indicates building objects, which may be damaged if the fault will be reactivated 61

Figure 2-60. Risk evaluation for fractures and cracks for the three Stages................................61

Figure 2-61. Fault slippage after hydration 62

Figure 2-62. Area of old shallow exploitations and possible damaged objects in the Anna mine area 62

Figure 2-63. Risk evaluation of sinkholes for the three Stages..63

Figure 2-64. Predicted uplifts for Candín mine 63
Figure 2-65. Risk evaluation for uplift 64
Figure 2-66. Chloride concentration measures in discharge points versus (1) PNEC long-term, (2) Drinking standard, and (3) PNEC short-term 65
Figure 2-67. Simulated contaminant concentration at the surface aquifer base after 30 years 66
Figure 2-68. Reactive transport modelling results for (a) Cl after 30 years, and (b) SO_4 after 50 years 66
Figure 2-69. Risk analysis for groundwater pollution around Rydułtowy-Anna Mining Complex 67
Figure 2-70. Installed pumping systems in Mosquitera and Pumarabule Mines 68
Figure 2-71. Risk evaluation for floods 69
Figure 2-72. Risk analysis of pollution of aquifers 70
Figure 2-73. Schematic cross-section showing the different flooding stages of Mosquitera and Venturo-Sotón mines. Scales not real, scheme just interpretative 70
Figure 2-74. Risk analysis for flooding of other mines 71
Figure 2-75. Zinc SSDs for PS6 (Rydułtowy-Anna Mining Complex mine)..................................72
Figure 2-76. Sulphates concentration measures in discharge points versus (1) PNEC long-term, (2) Drinking standard, and (3) PNEC short-term 73
Figure 2-77. Risk evaluation for zinc (PS4 and PS6) and manganese (PS1)...............................73
Figure 2-78. Risk evaluation for iron 74
Figure 2-79. Risk evaluation for chlorides in PS1 74
Figure 2-80. Risk evaluation for sulphates 75
Figure 2-81. Risk analysis for iron at Mosquitera and Pumarabule Mines...................................76
Figure 2-82. Simulation distribution of methane concentration in former ventilation network and goafs with VentGraph-Plus 77
Figure 2-83. Risk evaluation of gas migration to the surface 77
Figure 2-84. Medium risk area for gas migration to the surface 78
Figure 2-85. Simulation at the end of methane emission (2033)...79
Figure 2-86. Risk evaluation for accumulation of gas in the mine during the closure process........79
Figure 2-87. Risk evaluation for radon 80
Figure 2-88. Scale of consequences according to the economic impact of losses as defined by mining insurance companies. 82
Figure 2-89. Likelihood rating. 82
Figure 2-90. Risk matrix (IEC/ISO 31010, 2009). 83
Figure 2-91. Scale of risks. 83
Figure 2-92. Groundwater contamination Bowtie diagram..84
Figure 2-93. Interrelationship of the Risk Components 85
Figure 2-94. Bowtie Diagram of Rising Groundwater 85
Figure 2-95. Distribution of investments...90
Figure 2-96. Cash flows of the treatment strategies 90
Figure 2-97. Spider graph for the main variables to which NPV is more sensitive........................90
Figure 2-98. Monte Carlo analysis or the NPV of the cost analysis of the selected treatment options 91
Figure 2-99. Distribution of investments...92
Figure 2-100. Cash flows of the treatment strategies 92

Figure 2-101. Spider graph for the main variables to which NPV is more sensitive 92
Figure 2-102. Monte Carlo analysis or the NPV of the cost analysis of the selected treatment options 93

LIST OF TABLES

Table 2-1. Classification of mining areas due to allowed deformation ratios 22

Table 2-2. Limit values for the relevant pollutants in the discharged water 24

Table 2-3. Results of simulated mine inflows compared to the field data at the two mines 33

Table 2-4. Critical Controls/Risk Treatment Options 86

Table 2-5. Presentations given at the mining Congress 96

3 GLOSSARY

AA-EQS	Annual Average Environmental Quality Standards
AMD	Acid Mine Drainage
AMM	Abandoned Mine Methane
BAT	Bioavailability tool
CESR	Cost Effective Sulphates Removal
COD	Chemical Oxygen Demand
DMT	DMT GmbH & CO. KG
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
EQS	Environmental Quality Standards
EXETER	The University of Exeter
FEFLOW	Finite Element subsurface FLOW and transport system
FMEA	Failure Mode and Effects Analysis
GIG	Glowny Instytut Gornictwa
GIS	Geographic Information System
HUNOSA	Hulleras del Norte, S.A.
IMPERIAL	Imperial College of Science, Technology and Medicine
Ineris	Institut National de l'Environnement et des Risques Ineris
IMG PAN	Instytut Mechaniki Gorotworu – Polskiej Akademii Nauk
LCA	Life Cycle Assessment
M_{des}	Desorbed Methane
M_{wt}	Secondary Methane
NPV	Net Present Value
PAEC	Potential Alpha Energy Concentration
PGG	Polska Grupa Górnicza Sp. z.o.o.
PNEC	Predicted No Effect Concentration
PRB	Permeable Reactive Barriers
PSI	Persistent Scatter Radar-interferometry
SPM	Suspended Particular Matter
SRK	Spółka Restrukturyzacji Kopalń
TDS	Total Dissolved Solids
UNIOVI	Universidad de Oviedo
VSB	Vysoka Skola Banska – Technicka Univerzita Ostrava
WHAM	Windermere Humic Acid Model
WFD	Water Framework Directive

REFERENCES

Adams, R., & Younger, P. L. (2001). A strategy for modeling ground water rebound in abandoned deep mine systems. Ground Water, 39(2), 249-261.

Águeda, J.A., Bahamonde, J.R., Barba, F.J., Barba, P., Colmenero, J.R., Fernández, L.P., Salvador, C.I., Vera, C. (1991). Depositional environments in Westphalian coal-bearing successions of the Cantabrian Mountains, northwest Spain. In: Bertrand, P. (Ed.), Coal: Formation, Occurrence and Related Properties. Bulletin de la Société Géologique de France, vol. 162, pp. 325– 333.

Álvarez, R., Ordóñez, A., De Miguel, E., and Loredo, C. (2016). Prediction of the flooding of a mining reservoir in NW Spain. Journal of environmental management, 184, 219-228.

Anderson, M. P. and Woessner, W. W. (1992). Applied groundwater modeling: simulation of flow and advective transport. Academic press.

Antoine, F. (2010). Modélisation de scénarios accidentels de rejet de gaz inflammable au droit des évents du bassin du Nord Pas de Calais. Rapport INERIS pour le compte de Géoderis référencé INERIS-DRA-10-113798-07530C du 25/08/2010.

Arche (2014). The Lead BLM SSD Normalization Tool. Version 1.0.0. Ghent University, KTH and ILZRO. 2014. Downloaded on [01/05/2018] from http://www.leadBLM.com.

Balistrieri, L.S. & Mebane, C.A. (2014). Predicting the toxicity of metal mixtures. Sci Total Environ, 466-467, 788-799.

Banks, D. (2001): A Variable-Volume, Head-Dependent Mine Water Filling Model. Ground Water, 39 (3): 36.

Barba, P., Heredia, N., & Villa, E. (1991). Estratigrafía y edad del grupo Lena en el sector de Lois-Ciguera (Cuenca Carbonífera Central, NO de España). Revista de la Sociedad Geológica de España, 4, 61-77.

Barenblatt, G. I., Zheltov, I. P., & Kochina, I. N. (1960). Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks Prikl. Mat. Mekh., 24(5), 852– 864.

Bondaruk, J. et al. (2013). Management of mine water discharges to mitigate environmental risks for post-mining period (MANAGER). Directorate-General for Research and Innovation, European Commission.

Bukowski, P. (2011) Water Hazard Assessment in Active shafts in Upper Silesian Coal Basin Mines. Mine Water and the Environment, 30: 4, p. 302-311

Bula, Z. & Zaba, J. (2005). The tectonic position of the Silesian Coal Basin against the background of Precambrian and Lower Paleozoic ground. Proc. In LXXVI Scientific Meeting of the Polish Geological Society 'Geology and issues of protection of the environment in the region "Upper-Silesian", 14–42

Burgess-Limerick R, Horberry T & Steiner L (2014) Bow-tie analysis of a fatal underground coal mine collision, Ergonomics Australia. 2014; 10:2.

Chapman, P.M. & Wang, F.Y. (2000). Issues in ecological risk assessment of inorganic metals and metalloids. Hum Ecol Risk Assess, 6(6), 965-988.

COMSOL (2013). COMSOL Multiphysics user's guide, p 1356

Cowan, W.R.; Mackasey, W.O. & Robertson, J. (2010). The Policy Framework in Canada for Mine Closure and Management of Long-term Liabilities. National Orphaned - Abandoned Mines Initiative, Canada. Retrieved from: http://www.abandoned-mines.org/pdfs/PolicyFrameworkCanforMinClosureandMgmtLiabilities.pdf

Daqing L. (2017). Numerical method for analyzing fault slip tendency under fluid injection with XFEM. Politecnico di Milano. Ph. D. Course in mathematical models and methods for engineering.

De Ruiter A & Guldenmund F (2016) The Bowtie Method: A Review, Safety Science, 88 pp 211-218.

De Schamphelaere, K. A. C., Nys, C. & Janssen, C. R. (2014). Ecotoxicity of lead (Pb) to freshwater green algae: development and validation of a bioavailability model and inter-species sensitivity comparison. Aquat Toxicol, 155, 348-359.

De Schamphelaere, K.A.C. (2010). Development and validation of biotic ligand model for chronic toxicity of Pb to fish and invertebrates. Report prepared for ILZRO, Durham, NC, USA.

De Schamphelaere, K. A. C., Heijerick, D. G. & Janssen, C. R. (2002a). Refinement and field validation of a biotic ligand model predicting acute copper toxicity to Daphnia magna. Comp Biochem Physiol Part C: Toxicol Pharm, 133, 243-258.

De Schamphelaere, K. A. C. & Janssen, C. R. (2002b). A Biotic Ligand Model Predicting Acute Copper Toxicity for Daphnia magna:☐ The Effects of Calcium, Magnesium, Sodium, Potassium, and pH. Environ Sci Technol, 36, 48-54.

Degas, M. (2007). Bassin minier d'Aubin-Decazeville (Aveyron). Contribution à la réalisation d'un Plan de Prévention des Risques Miniers. Evaluation et cartographie des aléas liés aux mouvements de terrain. Rapport d'étude INERIS référencé DRS-07-78273-04592A du 20/12/2007.

Degas, M. (2012). Bassin minier d'Aubin-Decazeville (12). Complément à l'étude d'analyse et de cartographie des aléas « mouvement de terrain » relatif aux mines de fer. Rapport d'étude INERIS référencé DRS-12-129828-07804A du 13/12/2012.

Di Toro, D. M., Allen, H. E., Bergman, H. L., Meyer, J. S., Paquin, P. R. & Santore, R. C. (2001). Biotic ligand model of the acute toxicity of metals. 1. Technical Basis. Environ Toxicol Chem, 20, 2383-2396.

Didier, C. (2009). Postmining Management in France: Situation and Perspectives. Risk Analysis, 29(10), 1347-1354. doi: 10.1111/j.1539-6924.2009.01258.x

Diersch, H. J. G. (2013). FEFLOW: finite element modeling of flow, mass and heat transport in porous and fractured media. Springer Science & Business Media.

Duda, A., Krzemień, A. (2018). Forecast of methane emission from closed underground coal mines exploited by longwall mining – A case study of Anna coal mine. Journal of Sustainable Mining. Volume 17, Issue 4, Pages 184-194.

Durucan, S. et al. (1995). Environmental simulation and impact assessment system for the mining industry (ESIAS). Directorate-General for Research and Innovation, European Commission.

Dziurzyński, W. (1998). Prognozowanie procesu przewietrzania kopalni głębinowej warunkach pożaru podziemnego. Studia Rozprawy Monografie, 56.

Dziurzyński, W. (2002). Symulacja numeryczna procesu przewietrzania sieci wentylacyjnej kopalni Studies. Kraków: IMG PAN.

Dziurzyński, W., Krach, A., & Pałka, T. (2018). Shearer control algorithm and identification of control parameters. Arch. Min. Sci., 63(3), 537-552.

Dziurzyński, W., Krach, A., Krawczyk, j., & Pałka, T. (2005). Walidacja modelu matematycznego przewietrzania kopalni stosowanego w programie VentMet z wykorzystaniem bazy danych pomiarowych wybranego rejonu wentylacyjnego KWK. Prace IMG PAN, 7(1-2).

Dziurzyński, W., Krach, A., Pałka, T., & Wasilewski, S. (2008). Walidacja programu VentZroby z wykorzystaniem wyników eksperymentu „in situ" i z zastosowaniem nowych algorytmów przygotowania danych wejściowych. Prace IMG PAN, 10(1-4).

Dziurzyński, W., Krawczyk, J., & Pałka, T. (2008). Computer simulation of air and methane flow following an outburst in transport gallery D-6, bed 409/4. The Journal of the Southern African Institute of Mining and Metallurgy, 108, 139-145.

Dziurzyński, W., Pałka, T., & Wasilewski, S. (2015). Investigation of the parameters of the air flow in the longwall area for validation of the VentZroby simulation software. 37th International Symposium, on the Application of Computers and Operations. Fairbanks (USA).

EU Directive on Environmental Quality Standards. (2008). *Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy*. Official Journal L 348, 24/12/2008 pp. 84 - 97. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0105

EU Freshwater Fish Directive. (2006). *Directive 2006/44/EC of the European Parliament and of the Council on the quality of fresh waters needing protection or improvement in order to support fish life*. Official Journal L 264, 25/09/2006 pp. 20 - 31. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:264:0020:0031:EN:PDF

EU Ground Water Directive. (2006). *Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration*. Official Journal L 372, 27/12/2006 pp. 19 - 31. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32006L0118

EU Mining Waste Directive. (2006). *Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC - Statement by the European Parliament, the Council and the Commission*. Official Journal L 102, 11/04/2006 pp. 15 - 34. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0021

EU Water Framework Directive. (2000). *Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy*. Official Journal L 327, 22/12/2000 pp. 0001 - 0073. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

European Commission. (2008). European Union Risk Assessment Report. Voluntary Risk Assessment of Copper, Copper II Sulphate Pentahydrate, Copper(I)Oxide, Copper(II) Oxide, Dicopper Chloride Trihydroxide. European Commission, Brussels, Belgium.

European Commision. (2003). Technical Guidance Document on Risk Assessment in support of Commission Directive 93/67/EEC on Risk Assessment for new notified substances. EUR 20418 EN/2. European Commission Joint Research Centre. Office for Publications of the European Communities, Luxembourg.

European Copper Institute. (2008). May 2007-Chronic copper BLM. User friendly version of the chronic copper BLM. Available via Katrien Delbeke. European Copper Institute, Brussels, Belgium.

FAO. (2013). Water quality for agriculture. Food and Agriculture Organization, Irrigation and Drainage Papers. http://www.fao.org/docrep/003/t0234e/t0234e00.htm

Fernández, L.P., (1995). El Carbonífero. In: Aramburu, C., Bastida, F. (Eds.), Geología de Asturias. Ediciones TREA, Principado de Asturias, Spain, pp. 63–80.

Foster PJ, Lyle G. (2013) Application of BowTie Analysis in Assessing the Risk of Major Hazards in the Mining Industry, 23rd World Mining Congress, Montreal, 12th - 14th Aug 2013.

Foster PJ & Severn R (2013) Roof Fall Major Hazard Analysis with Bowtie Diagrams, 35th International Conference of Safety in Mines Research Institutes, London, October.

Fuente-Alonso, P., Sáenz de Santa María Benedet, J.A., (1999). La tectónica y microtectónica de la Cuenca Carbonífera Central de Asturias. Vol. Homenaje a J. Truyols. Universidad de Oviedo. Trabajos de Geología 21, 121 – 140.

Gabala, J.M., Cmiel, S.R., Idziak, A.F. (2004). Environmental impact of mining activity in the Upper Silesian Coal Basin (Poland). Geologica Belgica (2004) 7/3-4: 225-229.

Gillies, A., Wala, M., A., & Wu, H. W. (2005). Simulation of the Effects of Inertisation of Fires on Mine Ventilation Systems. Eighth International Mine Ventilation Congress, (pp. 317-324). Brisbane (Australia).

Gmur, D. and Kwiecinska, B.K. (2002) Facies analysis of coal seams from the Cracow Sandstone Series of the Upper Silesia Coal Basin, Poland. International Journal of Coal Geology, 52: 1-4 p. 29-44

Gudmundsson A., Simmenes T.H., Larsen B., Philipp S.L., Effects of internal structure and local stresses on fracture propagation, deflection, and arrest in fault zones. Journal of Structural Geology 32 (2010) 1643–1655

Guide PPRT. (2007). Le plan de prévention des risques technologiques (PPRT). Guide méthodologique. Ministère de l'Ecologie du Développement de l'Aménagement Durables, 2007. Retrieved from http://www.developpement-durable.gouv.fr/Maitrise-de-l-urbanisation-PPRT,12775.html

Harbaugh, A. W. (2005). MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process (pp. 6-A16). Reston: US Department of the Interior, US Geological Survey.

Heikkinen, P.M., et al. (2008). Mine Closure Handbook: Environmental Techniques for the Extractive Industries. Geological Survey of Finland, Technical Research Center of Finland, Outokumpu Oyj and Finnish Road Enterprise and Soil and Water Ltd. Vammalan Kirjapaino Oy, Finland. Retrieved from: http://arkisto.gtk.fi/ej/ej74.pdf

Herrero, C.; Muñoz, A. & Catalina, J.C. (2012). Prediction and monitoring of subsidence hazards above coal mines (PRESIDENCE). Directorate-General for Research and Innovation, European Commission.

IEC/ISO 31010. (2009). *Risk management - Risk assessment techniques*. International Electrotechnical Commission / International Organization for Standardization.

ICMM. (2007a). MERAG: Exposure Assessment: Exposure assessment using modelled and measured data. Fact sheer 02. The International Council on Mining and Metals (ICMM). EuroMetaux. London.

ICMM. (2007b). MERAG: Effect Assessment: Data compilation, selection and derivation of PNEC values for the risk assessment of different environmental compartments (Water, STP, soil, sediment). Fact sheer 03. The International Council on Mining and Metals (ICMM). EuroMetaux. London.ISO 31000. 2018. Risk management-Guidelines. International Organization for Standardization.

IGME (2011). Estudio sobre la inundación de los pozos mineros en la zona Candín (Valle del Nalón).

Ineris (2018). GUIDE Evaluation des aléas miniers Guide méthodologique.. INERIS-DRS17-164640-01944A (https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/Ineris-Guide_Aleas_miniers_0.pdf).

Ineris (2016). Évaluation de l’aléa « Gaz de mine ». Guide méthodologique. INERIS-DRS-15-149493-10366B (https://www.ineris.fr/fr/evaluation-de-lalea-gaz-de-mine-guide-methodologique).

Ineris (2006). L’élaboration des Plans de Prévention des Risques Miniers. Guide méthodologique. Volet technique relatif à l'évaluation de l'aléa. Les risques de mouvements de terrain, d'inondations et d'émissions de gaz de mine. Rapport d’étude INERIS référencé DRS-06-51198/R01 du 04/05/2006. Contribution de différents organismes.

Ineris. (2006). L’élaboration des Plans de Prévention des Risques Miniers. Guide méthodologique. Volet technique relatif à l'évaluation de l'aléa. Les risques de mouvements de terrain, d'inondations et d'émissions de gaz de mine. Rapport d’étude Ineris référencé DRS-06-51198/R01 du 04/05/2006. Contribution de différents organismes.

ISO 31000. (2018). *Risk management - Guidelines*. International Organization for Standardization.

Jardón, S., Ordóñez, A., Alvarez, R., Cienfuegos, P., & Loredo, J. (2013). Mine water for energy and water supply in the Central Coal Basin of Asturias (Spain). Mine water and the environment, 32(2), 139-151.

Jha, B., Juanes, R. (2014). Coupled multiphase flow and poromechanics: A computational model of pore pressure effects on fault slip and earthquake triggering. Water Resources Research, 50:3776–3808.

Joy J & Kizil G (2009), Acceptable Risk: A Matter of Establishing Adequate Control. Stage 2 Final Report on Project 15011, Australian Coal Association Research Programme: Brisbane

Julivert, M., Fontboté, J.M., Ribeiro, A., Conde, L., (1972). Mapa tectónico de la Península Ibérica y Baleares. Instituto Geológico y Minero de España (IGME), Madrid, Spain.

Kędzior, A., Gradzinski, R., Doktor, M. & Gmur, D. (2007) Sedimentary history of a Mississippian to Pennsylvanian coal-bearing succession: an example from the Upper Silesia Coal Basin, Poland. Geological Magazine, 144: 3, p. 487-496

Kędzior, S. (2015). Methane contents and coal-rank variability in the Upper Silesian Coal Basin, Poland. International Journal of Coal Geology, 139, p. 152-164.

Kempster, P.L., Van Vliet, H.R. & Kuhn, A. (1997). The need for guidelines to bridge the gap between ideal drinking water quality and that quality which is practically available and acceptable. *Water S.A.*, 23, 163 - 167.

Klinger, C. et al. (2011). Flooding management for underground coal mines considering regional mining networks (FLOMINET). Directorate-General for Research and Innovation, European Commission.

Kowalska, J.B., Mazurek, R., Gąsiorek, M. & Zaleski, T. (2018). Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination - a review. *Environmental Geochemistry and Health*, 40 (6), 2395 - 2420

Krause, E., Karbownik, M. (2019) Tests of methane desorption and emission from samples of hard coal in the context of mine closures through flooding. Journal of Sustainable Mining. Volume 18, Issue 3, Pages 127-133

Krause, E. (2018). Report on the implementation of the surface GHG emissions modelling at the selected PGG and HUNOSA mines, deliverable 2.4, INTERIM REPORT, project Merida, Management of environmental risks during and after mine closure.

Krzemień, A., Sánchez, A. S., Fernández, P. R., Zimmermann, K., & González Coto, F. (2016). Towards sustainability in underground coal mine closure contexts: A methodology proposal for environmental risk management. *Journal of Cleaner Production*, *139*, 1044–1056. https://doi.org/10.1016/j.jclepro.2016.08.149

Kurfeß D., Heidbach O. (2007). Coupled 3d finite element modeling of surface processes and crustal deformation: a new technical approach and parameter studies. International Symposium on Strong Vrancea Earthquakes and Risk Mitigation Oct. 4-6, 2007, Bucharest, Romania

Kwaśniewski M., Wang J. (1994). Symulacja komputerowa eksploatacji pokładu węgla systemem ścianowym z zawałem stropu, II. Zachowanie się uskoków poddanym wpływom eksploatacji. Zesz. Nauk. Pol. Śl. Gliwice, Z. 221.

Lagny, C., & Gombert, P. (2011). Evaluation de l'aléa « gaz de mine » pour l'ensemble des concessions du bassin minier d'Aubin-Decazeville (12). Rapport INERIS référencé DRS-11-121517-04850A du 17/10/2011.

Le Gal, N. (2012). Libération et migration du méthane depuis le charbon dans un contexte hydrogéologique post-minier: développement d'un protocole expérimental et approche numérique. Thèse, INERIS-Paris ENMP.

Loredo, C., Ordóñez, A., García-Ordiales, E., Álvarez, R., Roqueñi, N., Cienfuegos, P., Peña, A., & Burnside, N. M. (2017). Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. Science of the Total Environment, 576, 59-69.

Monomakoff, A. (1978). Dangers résultant de la présence du grisou dans l'atmosphère de la mine. Rapport CERCHAR "Grisou – Grisoumétrie – Anémométrie", CTO-JLi/MB 72-76-38, 1978.

Muñoz, J.E. and González, D. (2011). Formulación de observaciones y sugerencias a la propuesta de proyecto de plan hidrológico. HUNOSA (unpublished).

Muñoz de Fraga, J. E. (2015). Repercusión técnica y ambiental de la inundación de explotaciones de carbón subterráneas: Pozo Tres Amigos y Unidad Pumarabule-Mosquitera. PhD Thesis. University of Oviedo.

Nelson W.J. (1981). Faults and their effect on coal mining in Illinois. Illinois State Geological Survey, Natural Resources Building.

Neuman, S. P., and Wierenga, P. J. (2003). Comprehensive Strategy of Hydrogeologic Modeling and Uncertainty Analysis for Nuclear Facilities and Sites.

Neznal M. et al. (2004): The new method for assessing the radon risk of building sites.- Czech. Geol. Survey Special Papers, 47. p., CGS Prague.

Nys, C., Janssen, C.R., Mager, E.M., Esbaugh, A.J., Brix, K.V., Grosell, M., Stubblefield, W.A., Holtze, K. & De Schamphelaere, K.A.C. (2014). Development and validation of a biotic ligand model for predicting chronic toxicity of lead (Pb) to Ceriodaphnia dubia. Environ Toxicol Chem, 33(2), 394-403.

Nys, C., Van Regenmortel, T., Janssesn, C.R., Oorts, K., Smolders, E & De Schamphelaere, K.A.C. (2017). A framework for ecological risk assessment of metal mixtures in aquatic systems. Environ Toxicol Chem, 37(3), 623-642.

Ordóñez A, Andrés C, Álvarez R, Jardón S (2010). Aprovechamiento de las aguas subterráneas como recurso hídrico y energético. Seguridad y Medio Ambiente (Fundación Mapfre) 118:46–60

Ordóñez, A., Jardón, S., Álvarez, R., Andrés, C. and Pendás, F., (2012). Hydrogeological definition and applicability of abandoned coal mines as water reservoirs. J. Environ. Monit. 14, 21272–365, Worthington.

Pastor, J.; Klinger, C. & Talbot, C. (2008). Optimisation of mine water discharge by monitoring and modelling of geochemical processes and development of measures to protect aquifers and active mining areas from mine water contamination (WATERCHEM). Directorate-General for Research and Innovation, European Commission.

Parkhurst, D.L. & Appelo, C.A.J. (2013). User guide to PHREEQC-version 3: Description of input and examples for PHREEQC version 3-A computer program for speciation, batch reaction, one dimensional transport and inverse geochemical calculations, U.S. Geological Survey Techniques and Methods, Book 6 Modelling Techniques, Chapter 43, Section A Groundwater, 497. https://pubs.usgs.gov/tm/06/a43/pdf/tm6-A43.pdf.

Pendás, F., & Loredo, J. (2006). El agua en los procesos de cierre de minas en Asturias. Proceedings of Reunión Científico-Técnica "Gestión del agua en los procesos de cierre de minas". ETS Ingenieros de Minas, Universidad de Oviedo.

Pérez-Estaún, A., Bastida, F., Alonso, J. L., Marquínez, J., Aller, J., Alvarez-Marrón, J., Marcos, A and Pulgar, J. A. (1988). A thin-skinned tectonics model for an arcuate fold and thrust belt: the Cantabrian Zone (Variscan Ibero-Armorican Arc). Tectonics, 7(3), 517-537.

Piedad-Sánchez, N., Suárez-Ruiz, I., Martínez, L., Izart, A., Elie, M., Keravis, D., (2004). Organic petrology and geochemistry of the Carboniferous coal seams from the Central Asturian Coal Basin (NW Spain). International Journal of Coal Geology 57, 211–242

Pilecka E., Szermer-Zaucha R. (2016). Metody oceny oddziaływania wstrząsów pochodzenia górniczego na budynki, Zeszyty Naukowe IGSMiE PAN, Kraków

Pokryszka, Z. (2004). Dégagement gazeux de charbon ennoyé. Journée technique des Charbonnages de France. Freming-Merlebach, 23 juin 2004.

Pokryszka, Z. (2007). Bassin houiller du Nord Pas-de-Calais. Définition de l'aléa « gaz de mine » en vue de la réalisation d'un Plan de Prévention des Risques Miniers. Rapport méthodologique. Rapport référencé INERIS DRS-08-90082-08361A du 22 décembre 2007.

Pokryszka, Z. (2016). Evaluation de l'aléa « Gaz de mine ». Guide méthodologique. Rapport INERIS DRS-15-149493-10366B du 26/02/2016.

Pokryszka, Z., & Krause, E. (2007). Methane emissions from flooded coal seams in abandoned mines in the light of laboratory investigations. Mining and Environment N°IV/2007, ISSN 1643-7608, pp. 205-212.

Pokryszka, Z., & Mouilleau, Y. (2002). Sondages de décompression pour la concession De Wendel. Préconisations pour leur réalisation, définition de leur équipement en surface et étude du risque pour la phase de fonctionnement. Rapport INERIS-DRS-02-27667/R01bis du 30 janvier 2002.

Pokryszka, Z., Tauziede, C., Lagny, C., & Guise, Y. (2005). Gas Migration from Closed Coal Mines to the Surface. Risk assessment Methodology and Prevention Means. Symposium Post-Mining 2005, November 16-17. Nancy.

Połoński, M., Pawluk, K., Rybka, I. (2017). Optimization Model for the Design of Multi-layered Permeable Reactive Barriers. IOP Conference Series: Material Science Engineering. 245, pp. 8

Pöttgens, J. J. E. (1985): Bodenhebung durch ansteigendes Grubenwasser. 6. Internationaler Kongress für Markscheidewesen. Harrogate 1985, Tagungsband S. 928 – 938.

Pritchard, C. (2010). Validation of the Ventgraph program for use in metal/non-metal mines. 13 th US Mine Ventilation Symposium. Sudbury (Canada).

Pulles, W. (2008a). Best Practice Guideline G4: Impact Prediction. Department of Water Affairs and Forestry, Republic of South Africa. Retrieved from: http://www.bullion.org.za/documents/g4-impact-prediction.pdf

Pulles, W. (2008b). Best Practice Guideline G5: Water Management Aspects for Mine Closure. Department of Water Affairs and Forestry, Republic of South Africa. Retrieved from: http://www.bullion.org.za/documents/g5-water-management-aspects-for-mine-closure.pdf

Reason J (1997), Managing the Risk of Occupational Accidents, Ashgate Publishing, Aldershot:UK.

Robinson R (2000) Mine Gas Hazards in the Surface Environment, Mining Technology, 109 (3), pg 228-236.

Rȯzkowski, A. & Rȯzkowski, J. (1994) Impact of mine waters on river water quality in the Upper Silesian Coal Basin. International Mine Water Association. Proceedings of the 5th International Mine Water Congress, Nottingham, UK. September, 1994.

Rozkowski, A. (1995). Factors contributing the groundwater conditions of the carboniferous strata in the upper Silesian Coal Basin, Poland. Annales Societatis Geologorum Poloniae Vol. 64: 53 – 66.

Rüdel, H., Díaz Muñiz, C. & Garelick, H. (2015). Consideration of the bioavailability of metal/metalloid species in freshwaters: experiences regarding the implementation of biotic ligand model based approaches in risk assessment frameworks. Environ Sci Pollut Res, 22, 7405-7421.

Salmon, R. (2007). Bassin houiller du Nord Pas-de-Calais – Définition et cartographie de l'aléa « mouvements de terrain » en vue de la réalisation d'un Plan de Prévention des Risques Miniers. Zone 1. Rapport INERIS DRS-07-90083-17657A PROJET du 22/12/2007.

Santore, R. C. & Ryan, A.C. (2015). Development and application of a multi metal multi biotic ligand model for assessing aquatic toxicity of metal mixtures. Environ Toxicol Chem, 34(4), 777-787.

Sattari A., Eaton D. (2014). Finite element modelling of fault stress triggering due to hydraulic fracturing. GeoConvention: FOCUS adapt, refine, sustain.

SCHER. (2009). Voluntary Risk Assessment on Lead and its compounds. Environmental Part. Scientific Committee on Health and Environmental Risks. European Commission, Brussels, Belgium.

Sherwood, J. M., & Younger, P. L. (1997). Modelling groundwater rebound after coalfield closure. In Proceedings of the 28 th congress of the international association of hydrogeologists, Nottingham, UK, AA Balkema, Rotterdam (Vol. 1).

Sroka A., Preuβe A., Tajduś K., Misa R., (2016). Gutachterliche Stellungnahme zum Einfluss möglicher Grubenwasserregulierungsmaßnahmen auf die Abwasserinfrastruktur der Emschergenossenschaft Teil 1/1: Markscheiderische Beurteilung. Raport. Non-published.

Sroka A., Tajduś K., Misa R., (2017). Gutachterliche Stellungnahme zur Auswirkung des Grubenwasseranstiegs im Ostfeld des Bergwerkes Ibbenbüren auf die Tagesoberfläche. Raport. Non-published.

Stockdale, A., Tipping, E., Fjellheim, A., Garmo, Ø.A., Hildrew, A.G., Lofts, S., Monteith, D.T., Ormerod, S.J. & Shiland, E.M. (2014). Recovery of macroinvertebrate species ricness in acidified upland waters assessed with a field toxicity model. Ecol Indic, 37B, 341-350.

Stockdale, A., Tipping, E., Lofts, S., Ormerod, S.J., Clements, W.H. & Blust, R. (2010). Toxicity of proton-metal mixtures in the field: Linking stream macroinvertebrate species diversity to chemical speciation and bioavailability. Aquat Toxicol, 100(1), 112-119.

Szwedzicki, T. (2001). Program for mine closure. Mineral Resources Engineering, 10(3), 347–364.

Tajduś A., Cała M., Tajduś K. (2018). Seismicity and rock burst hazard assessment in fault zones: a case study. Arch. Min. Sci. 63, 3, 747-765

TGD. (2003). Technical guidance document on risk assessment. Part II. Risk Assessment European Chemicals Bureau. European Commission, Ispra.

TGD. (2007). Proposed EQS for Water Framework Directive Annex VIII substances: iron (total dissolved). Science Report SC040038/SR9. Environment Agency, Bristol.

Tipping, E. & Lofts, S. (2015). Testing WAM-FTOX with laboratory toxicity data for mixtures of metals (Cu, Zn, Cd, Ag, Pb). Environ Toxicol Chem, 34(4), 788-798.

Tipping, E. & Lofts, S. (2013). Metal mixture toxicity to aquatic biota in laboratory experiments: Application of the WHAM-FTOX model. Aquat Toxicol, 142-143, 114-122.

Toth, J. (1963). A theoretical analysis of groundwater flow in small drainage basins. J. Geophys. Res. 68: 4795 – 4812.

USEPA. (2007). Framework for metals risk assessment. Technical Report EPA 120/R-07/001. Risk Assessment Forum. Washington, DC.

Van Regenmortel, T., Nys, C., Janssen, C.R., Lofts, S. & De Schamphelaere, K.A.C. (2017). Comparison of four methods for bioavailability-based risk assessment of mixtures of Cu, Zn and Ni in freshwater. Environ Toxicol, 36(8), 2123-2138.

Van Sprang, P.A., Verdnock, F.A.M., Van Assche, F., Regoli, L. & De Schamphelaere, K.A.C. (2009). Environmental risk assessment of zinc in European freshwaters: a critical appraisal. Sci Total Environ, 407(20), 5373-5391.

Verdonck, F., Souren, A., van Asselt, M., Van Sprang, A. & Vanrolleghem, P. (2007). Improving Uncertainty Analysis in European Union Risk Assessment of Chemicals. Intgr Environ Assess Manag, 3(3), 333-343.

Wesołowski M. (2012). Określenie wpływu projektowanej eksploatacji na deformacje w rejonie uskoku Radzionkowskiego. (Determination of the influence of planned exploitation on deformations in the area of the "Radzionkowski" fault) Przegląd Górniczy T. 68, nr 4, pp.41-45.

Wesołowski M. (2016). Numerical modeling of exploitation relics and faults influence on rock mass deformations. Arch. Min. Sci., Vol. 61, No 4, pp. 893–906.

WHO. (2018). A global overview of national regulations and standards for drinking water. World Health Organization. Geneva. Licence: CC BY-NC-SA 3.0 IGO. pp. 104

WINDWARD. (2015). Biotic Ligand Model Windows® Interface, Research version 3.41.2.45: User's Guide and Reference Manual. WindWard, Environmental LLC. Washington, DC.

Wolkersdorfer, C. (2008). Water management at abandoned flooded underground mines: fundamentals, tracer tests, modelling, water treatment. Springer Science & Business Media.

Younger P.L., & Adams R. (1999). Predicting mine water rebound. Environment agency R&D technical report W179, Bristol

Younger, P. L., Banwart, S. A. and Hedin, R. S. (2002). Mine Water – Hydrology, Pollution, Remediation. 464 p.; Dordrecht (Kluwer).

Younger, P. L. (2002). Deep mine hydrogeology after closure – insights from the UK. – In: Merkel, B. J., Planer-Friedrich, B. & Wolkersdorfer, Ch.: Uranium in he Aquatic Environment. – p. 25–40, 1 fig., 2 tab.; Heidelberg (Springer).

Younger, P.L. (2011). Hydrogeological and geomechanical aspects of underground coal gasification and its direct coupling to carbon capture and storage. Mine Water and the Environment, 30(2), 127-140.

Zhang, J., & Shen, B. (2004). Coal mining under aquifers in China: a case study. International Journal of Rock Mechanics and Mining Sciences, 41(4), 629-639.

Zhang N.B., Liu C.Y., Yang P.J. (2016). Flow of top coal and roof rock and loss of top coal in fully mechanized top coal caving mining of extra thick coal seams. Arabian Journal of Geosciences 9 (6), 1-9.

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
– at the following standard number: +32 22999696 or
– by email via: https://europa.eu/european-union/contact_en

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1952 in all the official language versions, go to EUR-Lex at: https://eur-lex.europa.eu

Open data from the EU

The EU Open Data Portal (https://data.europa.eu/euodp/en/home) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

KI-NA-30-412-EN-N

The management of environmental risks during and after mine closure is a multi-hazard and multi-risk process that requires integration of interrelated environmental processes and combining their effects when considering hazard identification and risk characterisation.

MERIDA project designed and provided technical guidance on the implementation of the necessary investigations that should be undertaken to develop a sound and sustainable mine closure plan.

The aim was to minimise the environmental impacts and risks during the mine closure and post-closure periods in accordance with the general principle that the mine must take responsibility and minimise all risks that can be foreseen.

In practical terms, MERIDA provides a planning tool that allows the design of a logical, stepwise approach to mine closure that can be progressively refined during the post-closure period and allows to address all relevant environmental risks.

Main goals achieved by MERIDA were:

- Providing specific guidance on the issues that need to be considered when assessing the environmental impacts from coal mines at closure and post-closure stages.
- Identifying the physical and chemical processes that affect environmental risks during mine closure and post-closure period and establish monitoring and modelling methods that should be implemented to make reliable environmental impact predictions.
- Establishing an integrated risk assessment methodology.
- Providing a practical methodology that can be used for the evaluation of risk remediation measures in terms of their performance in risk reduction, practical implementation, and cost.

To illustrate the benefits of implementing the project results at the partner coal mines and communicate the findings to the coal mining community across Europe.

Publications Office
of the European Union