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Management of environmental risks during and after mine closure

MERIDA
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Best practice guideline:
Environmental impact prediction and risk management methodology for coal mine closure and post-closure

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The MERIDA Project: *The projects objective is to develop a methodology to manage environmental impacts and risks during and after coal mine closure and provide a generic tool that allows the industry to implement the methodology at any site. MERIDA will identify the short and long-term consequences of coal mine closure on the environment and define appropriate and financially feasible mitigation measures that guarantee acceptable risk levels according to the environmental conditions and surface occupation nearby the mines.*

More information about MERIDA may be found at www.meridaproject.com/

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1. The MERIDA Project

1.1 OBJECTIVES OF THE MERIDA PROJECT

The overall aim of the MERIDA (Management of Environmental Risk during and after Mine Closure) project was to identify and minimise the environmental impacts and risks during the mine closure and post-closure periods in accordance with the general principle that the mine operator must take responsibility and minimise all risks that can be foreseen.

The objectives were 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;
- Establish an integrated risk assessment methodology for the analysis and evaluation of these environmental risks;
- 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.
- Provide specific guidance on the process and the issues that need to be considered when assessing the environmental impacts from coal mines at closure and post-closure stages.

In line with the above the project has developed a risk based methodology for this purpose which is outlined in this document. This has involved specific case studies at a number of mine sites in Poland and Spain that closed during the course of the project. The process is generic thereby allowing the industry to implement the methodology at any site.

The specific risks that were focused on in this project were:

- Ground movement
- Gas Emissions (Methane and Radon)
- Groundwater
- Surface water

An ArcGIS database was also created with the modelling results integrated in the database with a web-based visualisation environment. This allows the visualisation and interpretation of the different environmental impacts for both the Polish and Spanish sites in relation to their spatial distribution and the sensitive receptors. The database was provided with an analytic tool in order to allow the user to study 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.

As with any major research project, the work undertaken was in the form of a series of work-packages focusing on the context, the modelling of the risks, the risk assessment and risk treatment. For information this is shown in Figure 1.1 below.

Work Package 1:

GIS TOOL DEVELOPMENT, COLLECTION AND ORGANISATION OF DATA

This work package established the overall framework for the collection and compilation of data related to environmental impacts during the coal mine closure and post-closure stages.

Case study sites were identified in Poland and Spain and background environmental data relating to water, soil and air quality collated. Laboratory tests to establish the degassing properties of coal under water pressure were carried to evaluate the long term gas flow after mine flooding.

A review was also carried out into the risk criteria for the key post closure risks of subsidence, surface/groundwater pollution, sediment/soil pollution and air pollution to establish a benchmark for environmental risk assessment.

Information and data on past environmental incidents in European coal mine regions was collated. A GIS based data management tool was also set up for the purpose of visualising the simulations and risks established in the project.

Work Package 2:

DEVELOPMENT OF ENVIRONMENTAL IMPACT ASSESSMENT MODELS FOR COAL MINE CLOSURE AND POST-CLOSURE PERIODS

This **work package** developed site specific issue based models that allowed quantitative evaluation of the principle environmental impacts during coal mine closure and post-closure periods in the Polish and Spanish case study mines.

The results of these models were used to demonstrate the functionality of the GIS based environmental management system developed in Work Package 1.

In particular this involved (i) using geo-mechanical and surface deformation modelling methods to evaluate the subsidence potential; (ii) using hydrological modelling software to simulate groundwater flow and solute transport; (iii) using aqueous water geochemistry software tools to model the surface water quality and pollutant bioavailability; (iv) modelling and estimating gaseous emissions to the surface from coal mines during closure and post- closure periods.

Work Package 3:

RISK EVALUATION

In this work package detailed risk assessments and evaluations of the key hazards (subsidence, ground/surface water and gaseous emissions) were carried out based on the results of the data collection and modelling previously undertaken.

These assessments were undertaken for both the Polish and Spanish mines and the risks evaluated using a risk matrix. Risk treatment strategies were identified for each considering the relationships between subsidence, gaseous, ground and surface water impacts. Bowtie analysis was used for this purpose

Work Package 4:

RISK MANAGEMENT AND REMEDIATION MEASURES

Within this work package performance of alternative risk treatment and mitigation strategies were evaluated in terms of the level of residual risk 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, NPV's were calculated, in order to determine the financial provisions required for closure and post-closure stages.

Work Package 5

DISSEMINATION

Activities 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 mine closure

Figure 1.1: The Structure of the MERIDA Project

1.2 STRUCTURE OF THE GUIDELINES

These guidelines are divided into three distinct parts.

The first Part (Section 2) looks at the principles of coal mine closure summarising elements of best practice in terms of shaft closure, gas hazard mitigation, waste rock and water treatment management. Examples are given of the different types of impact and risk that have occurred when these environmental hazards have been realised. As legislation differs across EU countries, a review of key risk criteria for the different environmental hazards is given so as to provide a baseline for any environmental risk assessment.

The second Part (Section 3) summarises the MERIDA risk management methodology. This is a risk assessment based planning tool that provides a step by step approach to mine closure that can be progressively refined during the post-closure period to address all relevant environmental risks. This tool is based around three main components (i) modelling of the risks (ii) risk assessment & (iii) evaluation and economic evaluation.

The final part (Appendix) outlines the results of the implementation of the risk management methodology (modelling, risk assessment and economic evaluation) at two case study sites, one in Poland and the other in Spain.

2. Mine Closure Risks

2.1 PRINCIPLES OF MINE CLOSURE

Planning for mine closure will start in the mine planning phase during feasibility studies, and is a requirement of individual countries and local authority's environment permitting systems and operating licences. Such planning can and will be updated throughout the lifetime of the mining operation reflecting changes in mining, expansion, and any unforeseen environmental impacts. Local communities and other stakeholders should be engaged throughout the process as they will have to live with the outcomes.

The objectives of the closure plan should be:

- Ensure the site is physically and chemically stable and safe for humans and wildlife.
- Encourage the re-establishment of a sustainable ecosystem.
- Ensure the land suitable for subsequent use.
- Minimise the economic loss to local communities and encourage sustainable economic development.
- Minimise the long-term remediation and monitoring costs.
- Ensuring adequate resources for a timely and cost efficient closure.
- Successful completion according to relevant authorities.
- Establish who is accountable post-closure.

Planning for closure will always be taken on a case by case basis, taken into account the specific characteristics, issues and hazards at each site. Closure criteria within Europe is closely linked with the conditions of planning permission for the mine. Closure of waste disposal facilities is covered by the European Union (EU) Mining Waste Directive (EU, Directive 2006/21/EC, 2006). This includes requirements for the establishment of a closure plan for the waste facilities (Article 12) and allocation of a financial bond to cover the estimated costs of closure and rehabilitation (Article14).

When closing an underground mine there are numerous hazards including:

- Shaft failure
- Subsidence
- Mine gas
- Fires
- Water pollution
- Trespassing
- Rubbish dumping
- Waste rock

The site closure strategy will incorporate measures to prevent such hazards from occurring. However, remediation and emergency measures must be put in place to limit their impact should they occur. In many me cases sites must also retain and maintain access infrastructure (e.g. for the reestablishment of mining, water level monitoring or water quality monitoring).

An environmental baseline study will be completed before the operation begins. This characterises the local environment and socio-economic factors. This baseline will be used in the environmental impact assessment (EIA) and/or environmental and social impact assessment (ESIA), but it can also be used as a comparison for environmental monitoring throughout the mining lifespan, and as a target for environmental management actions following mine closure.

Sections of the mine can be remediated as they stop being used. This is termed ‘progressive rehabilitation’. There are several befits to progressive remediation:

- It can reduce costs as contractors and equipment are already present on the site and it can reduce the need to handle material twice.
- It can reduce the time to remediate after closure.
- It results in a smaller un-remediated footprint at any one time, which can be more acceptable to local communities.
- It provides an opportunity to trial remediation options and demonstrate their efficacy.

There are several other innovative methods to reduce remediation costs. Examples include: co-designing remediation activities with resource recovery (e.g. recovering metals from mine waste prior to capping); upcycling mine waste (e.g. recovering ochre and using it directly as a commercially valuable product such as a pigment); and periodically modifying mining activities to lower the environmental impact of subsequent waste (e.g. mining of non-sulphide bearing minerals in order to create impermeable layers of such material upon acid rock drainage (ARD) producing mineral waste within a tailings repository) (Australian Government: Department of Industry, Tourism and Resources, 2006).

There has been a great deal of historic and recent experience in coal mine closure within Europe. There has also been a number of research projects undertaken to ascertain and document what might be considered best practice. This is summarised in the following sections on the specific issues of shafts, gases, waste rock and mine water.

2.1.1 SHAFT CLOSURE

Shaft closure has been the subject of recent research, in particular the RFCS funded MISSTER (Mine shafts: improving security and new tools for the evaluation of risks) project. Specific shaft closure guidelines were published from this project.

Shafts need treating post closure for the following reasons.

- Prevention of people and animals falling into abandoned shafts/adits
- Prevention of members of the public gaining unauthorised access to the mine
- Prevention of risks associated with subsidence which could damage existing structures in the impact zone
- Prevention of risk of collapse of the surface land
- Monitoring of gas discharges
- Offering long-term guarantees of stability and durability
- Preserving fauna, especially protected species

Each shaft will have individual properties and environmental setting so treatment objectives will often have to be site specific. The following information is necessary for this purpose.

Shaft Location

Locating the shaft to be treated is one of the first actions that must be undertaken. This is easy if the shaft is still in use or is easily visible in the field. If this is not the case mining maps can be compared with site plans and local maps. Often this still leaves an unacceptable level of uncertainty (tens to several tens of metres).

There are several different methods to increase the certainty which can be used in combination with each other. These include the compulsory disclosure of documents, investigation with local people, geophysical techniques, surface excavation and surveys.

Site Access

If there is direct access to the workings using existing infrastructure or low cost construction all treatments are possible. However, if the workings are very isolated and no heavy vehicles can be used the possible options are restricted. Treatment options are also restricted when the shafts are in infrastructure/buildings or the surface is encumbered.

Local Issues and Future Land Use

Issues need to be identified to establish the risks. For example; is the shaft close or in an urban environment? Or a building, road, infrastructure, frequently used path etc.

Shaft Geometry

The type and dimensions of the shaft opening control the possible treatment options. The size, shape and depth of the shaft determines the quantity of material needed for backfilling and design-sizing of other safety techniques. If the shaft opening is not visible archives or records may have the information. When a shaft is opened a suitable probe can be used to inspect it.

Condition of Mine Workings

If possible the shaft lining material, thickness and condition should be investigated, along with the lining contact with its surrounding. Any zones of collapse, backfill or areas which have been blocked off should be recorded. The whole shaft needs to be examined to determine the safety conditions. This will all feed into which treatment is appropriate. If access to the shaft is unsafe or not possible video cameras and laser/sonar techniques can be used.

Connections with Other Workings, Presence of Voids or Infrastructure

To successfully backfill a shaft the extent of connectivity with other openings (e.g. tunnels, shafts) must be known, as well as the connectivity with the main service area at the bottom of the shaft. It is also useful to know which connected workings have been backfilled or have collapsed, and which are cut off by barriers and which are open.

If the treatment techniques considered affect the perimeter of the shaft opening it is important to have knowledge of any infrastructure or pipes in immediate vicinity to the workings. If there is a risk of gas escape it is vital to know about any ducts or cavities that the gas could migrate into.

Geology

The geotechnical properties of the geology (and if applicable sediment) surrounding the shaft, as well as any such material in the wider impact zone need to be identified in order to establish the stability and anchoring conditions which are required for mine site closure activities.

All relevant cross-sections of the surrounding geology should be consulted and their geomechanical properties evaluated. If data are unavailable local outcrops should be studied, and in some cases test drilling and/or geophysical characterisation may be required.

It is often important to determine the nature and thickness of the mobile land surface (soil, backfill) as this can be vulnerable to collapse and is important to determining the right treatment.

If the shaft has previously been backfilled and compaction above the backfill is observed it may be advisable to assess its stability. This is often conducted by drilling cores and analysing the resultant material.

Hydrogeology

Water in the strata causes complications such as:

- Reduction in mechanical properties of strata
- Communications between aquifers
- Water pollution
- Possibility of flooding

The depth and thickness of the water table close to the shaft needs to be assessed to establish if that will impact the technique and materials to be used. It presence of any pollution vectors in the workings also needs to be assessed. If the water table is liable to rise or change significantly through the seasons, inundating the proposed safety structures, the correct material for the water chemistry will need to be used.

Degradation

Most materials used for shaft lining will undergo degradation in the natural environment, especially in saturated shafts No matter what material is used for shaft lining the material will eventually degrade, especially in saturated shafts and/or those which are exposed to low pH water. The specific timescale for such degradation depends on a range of factors.

Simply using plugs, linings and capping is often not the safest long term option, as these materials also degrade. Backfilling the whole shaft is usually the safest option as although backfill degradation can lead to long-term subsidence this is not as significant a failure as that which can occur from plugged/capped shafts. However backfilling must be done using best practice as the backfill material itself can undergo significant degradation and result in wider environmental damage due to greater ecotoxic metal release.

Mine Gas

Sometimes ancillary systems are needed to control gas. The maximum flow rate and composition of the gas must be assessed to determine the type of sealing technique, whether there should be an exclusion zone, if an ancillary system (vents, ventilation system) should be installed, or if a monitoring system is needed.

Preserving Access to the Underground Mine Workings

Preserving access to the underground workings increases costs and creates problems around maintenance and safety. However, in some cases it is necessary or even desirable. For example:

- Using mining voids as habitats for protected fauna
- Access to carry out supervisory or strengthening works
- If there is a possibility of the mine being re-opened in the future

If underground access is to be preserved the treatment should reduce to risks to acceptable parameters and the responsibilities of the owner, operator, local government and the state should be established.

Preserving Flora, Fauna and the Environment

If abandoned workings are used as a permanent or temporary habitat for protected species (European Directive 92/42/CEE) the type of closure selected should preserve both existing access and in situ conditions (temperature, humidity, atmosphere composition, etc.). Access can be preserved while preventing human entry using specific physical barriers, such as concrete grills. Such systems will require installation costs and require regular maintenance.

Liabilities need to be clearly established.

Costs

Costs that need to be considered are not just the initial treatment, but also the ongoing maintenance. Costs will vary between sites due to location, equipment used, material needed and other complications like maintain access or preserving the environment.

Treatments

Table 1: Best engineering solution depending failure or risk type

Failure/risk type	**Constructive solution**
Collapse of shaft filling material	➢ Insure robustness of the deep closure structure ➢ Clean the shaft before filling ➢ Choose suitable filling materials ➢ Control the filling of the shaft to prevent the creation of voids
Failure of shaft head	➢ insure the robustness of the existing cap ➢ for opened shaft, establish a capping well dimensioned able to resist especially to water pressure and/or surface overload ➢ reinforce the surrounding land by injection
Failure of shaft lining	➢ for opened shaft, check by inspection the state of degradation of the lining and reinforce the lining in case of degradation ➢ use backfilling method when possible ➢ reinforce the surrounding land by injection
Failure of deep closure structure	➢ design closure structure according to the applied loads ➢ clean the shaft before the filling
Failure due to water effect and/or particular geologic formation	➢ design capping taking into account possible water effect ➢ use filling material appropriate to mining water ➢ reinforce lining or soil to avoid water infiltration
Risk of subsidence	➢ use appropriate filling material ➢ control the filling of the shaft to avoid the creation of void
Risk of gas release	➢ establishment of event ➢ control of gas concentration

Shaft Fill

Shafts are filled to stop the risk of physical injury and falls, as well as reducing the risk of collapse. Backfilling strengthens the shaft lining by absorbing a proportion of the horizontal thrust from the surrounding rock. The level of the backfill should be measured for several years or while the mine is flooding. After filling there are still risks around ground movement and gas emissions.

Before filling there needs to be:

- A visual inspection
- Knowledge of any historical backfilling, including details of any associated problems with such activities
- Knowledge of underground connectivity to the shaft
- An assessment of current and potential gas emissions following backfilling
- An assessment of current and potential changes to hydrogeology and water quality following backfilling

Filling involves feeding granular material into the shaft using a conveyor, or directly from a lorry. The shaft, therefore, must be accessible for such infrastructure/vehicles.

To create a safe, water permeable column the materials should:

- Exhibit a grain size between 2 and 120 mm and grain median DM = 100 mm free of undersize particles;
- Exhibit a compression strength of at least 30 MPa;
- Be non-flammable;
- Not contain toxic compounds;
- Exhibit a low risk of leaching harmful and hazardous elements;
- Exhibit radioactivity beneath the relevant threshold level.

Rocks such as granite, gneiss, basalt or dolomite are often used. There is also a possibility to use a grainy material of different qualities (i.e. of low strength parameters and different grain size distribution), such as waste materials from coal or steel processing. Using them is economical, yet it requires additional tests.

It is essential to back-fill the first metres from the base of the shaft using coarse materials to guarantee a stable base for the superimposed back-fill, and avoid fine material flowing into the former works. All levels of the shaft with connections to workings should be back-filled using coarse material. These sections should start below the floor of the service area and block off the opening to the latter and continue up to an adequate height above the top of the service area. The same material is appropriate for filling water submerged shafts. The use of concrete may be appropriate in certain cases (reduction of voids, increased strength, capping block at the top to avoid any surface compaction).

During the back-filling operations, the alignment of back-filling conditions, the quantities of material deposited and the pre-defined quantities must be regularly verified by measuring the height of the back-fill. For water-submerged shafts, the water displaced by the back-fill may rise up and special precautions should be adopted for its removal (pumping) as the back-fill rises up the shaft.

Renewing Backfill

Additional material may need to be added to a previously filled shaft due to compaction, sliding or a sudden decoring of material in the shaft. This technique is sometimes used when an “accident” or an event occurs, requiring the rapid deployment of temporary safety measures.

The method is to pile additional backfilling material above the shaft, so that if a void forms in the backfill column the additional material will fill it. This method is most appropriate for a small volumne shaft, a diameter of <3 m and a depth of <100 m, which has previously been backfilled.

The material used should be of graded grain size, with a proportion of fine materials which can migrate in the event of movement in the shaft. The materials must be inert and non-flammable.

The volume of the backfill cone must be adapted to that of the shaft; the slope of the heap of back-fill must be adjusted and its diameter must exceed that of the shaft. For example, a minimum of three times the diameter of the opening.

Capping Slab

Shafts are capped if they present a risk for physical injury (falls) and/or if there is a risk of ground movement; espesically if there are occupied buildings around the perimeter of the shaft.

Before capping the following activites are recommended:

- Preliminary visual inspection, including establishment of the condition of back-fill of works
- Gas measurements and piezometric measurements
- A geological and geotechnical profile of the edges of the shaft (studies already performed or specific survey and drilling pressiometric cores) to establish depth of the firm land.
- A document search: cross section or plan of the mine-head, nearby infrastructure, technical or shallow tunnels, assessment of potential gas emissions

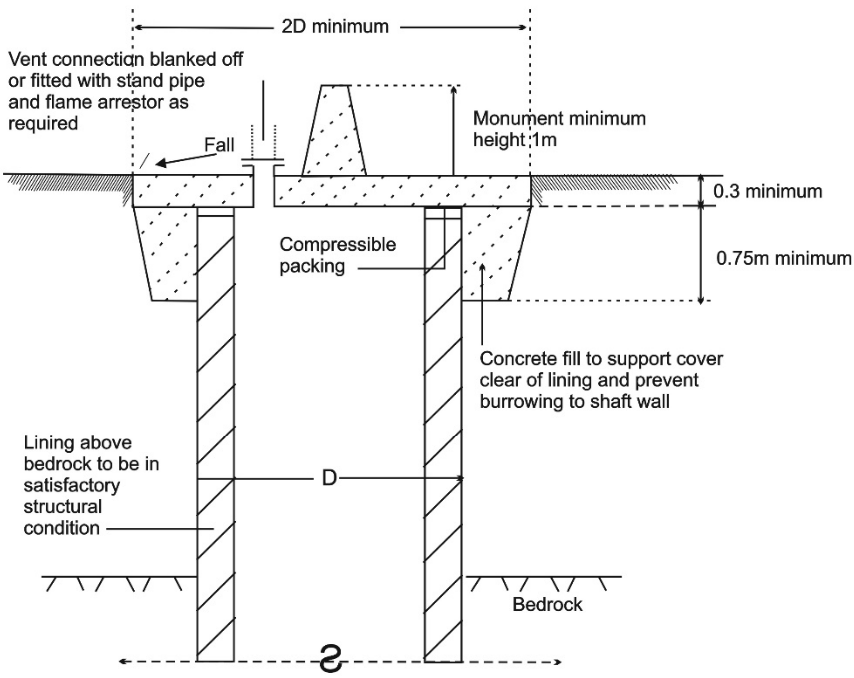
To use a cap there must be restistant land or a support structure within 5 m of the surface and vehicles access.

Capping involves installing reinforced concrete after clearing the top section and surrounding of the shaft. Stability of the capping slab is guaranteed through support on the surrounding land/former infrastructure which maintains it by reaction, and the bending/tensile strength of the reinforcing bars.

Capping does not remove the risk of mine gas and there is still a ground movement risk if there is a residual void underneath the slab. This technique is not appropriate if preserving protected species.

Maintenance of a capping slab can be repairing the is if it is incorrectly dimensioned and affected by ground movements and maintenance of gas vents if installed.

The capping slab is design-sized so that its own weight, that of the overload on the surface and any effects of decoring if the shaft is back-filled are taken up by the supports on the edge, and the bending/tensile strength of the constituent concrete.



Notes :
- Cover designed for superimposed load of 33kN/m^2
- RC slab grade C30 concrete minimum thickness 0.3m
- Cover to be marked with shaft reference number diameter and depth, and munument to be positioned centrally.

Figure 2.1: Example of outline diagram of a surface slab of the light or heavy duty type and of underground slabs installed at the top of a rocky outcrop (NCB, 1982)

For design-sizing, the ratio between thickness of the concrete and the greatest dimension (length) of the slab must be taken into account. The thickness must take into account inclusion of the reinforcement bars (frequently welded trellis) enabling the slab to withstand bending/tensile force. The coating and diameter of the reinforcing must comply with the calculation rules for reinforced concrete (former BAEL rules, Eurocode 2). The compression strength of the concrete is not a fundamental value: however, for its resistance over time classes superior or equal to C25/30 (standard EN 206-1) should be preferred. It is also strongly recommended taking account of environmental degredation (notably, when the water level is close to the capping slab) for the cement dosage.

The capping slab must be constructed such that it has sufficient dimensions to take into account ground movement which may also result in breakage of lining, or sudden decoring of back-fill for a recently filled shaft. Particular care should be paid to the external supports of the capping slab to avoid it becoming loose.

The calculation of stress must take into account surface effects, both permanent (notably suction in the case of sudden decoring of the shaft back-fill) and ad hoc (notably anticipated loading caused by passage of vehicles/plant).

On occasion, a manhole is required to check the level of the back-fill (previously filled shaft) or to take gas measurements (where there is potential for emission at the surface). A vent should also be constructured for works where gas emissions are predicted.

The calculation of stress must take account of surface effects, both permanent (notably suction in the case of sudden decoring of the shaft back-fill) and ad hoc (notably anticipated loading caused by passage of vehicles/plant).

On occasion, a manhole is required to check the level of the back-fill (previously filled shaft) or to take gas measurements (where there is potential for emission at the surface). A vent may prove necessary for works where gas emissions are probable.

Self-supporting Plug

A self supporting plug can be used to to remove ground movement risk when there is a presence of major challenges above, or in the imediate vicinity of the shaft (e.g. occupied building, road with traffic). It also combats the risk of physical injury.

Before installing the plug the same actions must be undertaken as when using a capping slab:

- Preliminary visual inspection, including establishment of the condition of back-fill of works
- Gas measurements and piezometric measurements
- A Geological and geotechnical profile of the edges of the shaft (studies already performed or specific survey and drilling pressiometric cores) to establish depth of the firm land.
- A documentary search: cross section or plan of the mine-head, nearby infrastructure, technical or shallow tunnels, assessment of potential gas emissions

There also must be vehicle access and resistant land within 20 m of the surface.

The treatment works by installing concrete to a determined depth within the shaft and utilising the geometric irregularities of the shaft lining to ensure that the cap withstands the shearing stress. There is no maintenance associated with a self-supporting plug but it is not suited to preseving protected species.

Self-support is guaranteed by resistance to shearing of the concrete on the shaft lining, which normally presents many irregularities. Satisfactory operation and durability of the cap are guaranteed if the structure is supported around the entire internal periphery of the shaft lining for optimum distribution of stress on the intrados generated by its weight. The quality of the lining, its interfacing with the land and the mechanical quality of the latter are also important aspects for retention of the cap over time.

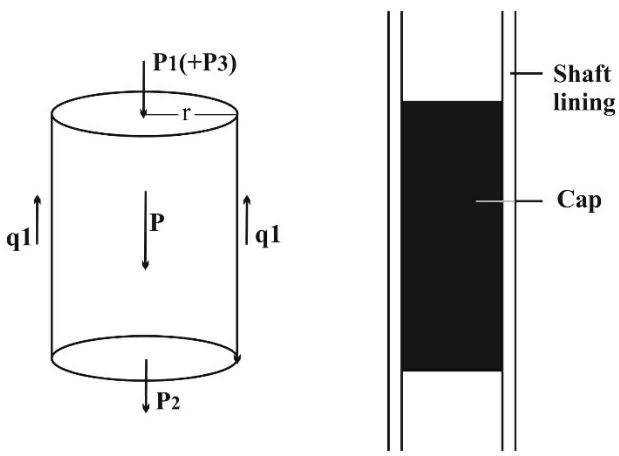


Figure 2.2: Principle of self-supporting cap with friction (shears strength) on the shaft lining

The cap is design-sized so that the shearing resistance at the cap/shaft contact point exceeds the weight of the cap, the weight of any back-fill above the cap, and suction in the event of sudden decoring of back-fill or surface overload. A safety factor of 3 must be taken into account for resistant and moving forces. The height of the cap cannot be less than twice the diameter of the shaft.

Preferably the concrete cap should be constructed in two phases: Installation of a pre-cap design-sized to support casting the column of concrete; Once the pre-cap is sufficiently strong (20 MPa in compression), a second casting is made as defined by the principles and hypothetical calculations used to design-size the cap.

The choice of material used to constitute the cap affects its design-sizing depending on the shearing resistance of the lining/cap interface (which depends on the nature of the binder and the condition of the lining). The compression strength of the concrete is not a fundamental value: however, for its resistance over time classes superior or equal to C25/30 (standard EN 206-1) should be preferred. It is also strongly recommended taking account of the environmental attack when calculating the quantity of cement (Standard EN P18-201, CCTG booklet 65, standard P18-011). Insertion by pipe is to be preferred for shallow caps to avoid segregation.

The choice of back-fill material above the cap also has a major influence on the design-sizing of the latter. Landfill of varied grain size (see “back-fill” information sheet) or lean concrete can be used.

Constructive techniques:

1. Installation of a pre-cap which is designed to support casting the column of concrete.
2. Once the pre-cap is sufficiently strong (20 MPa in compression), a second casting is made as defined by the principles and theoretical calculations used to design- size the cap.
3. Insertion by pipe is to be preferred for shallow caps to avoid segregation.

Anchored Plug/Closure

An anchored plug is used to reduce the risk of physical injury and falls, as well as the risk of ground movement when there are major challenges above or in the immediate vicinity of the shaft (e.g. occupied buildings, road with traffic).

To use this method the shaft must be accessible to vehicles there must be roadways or excess widths at shallow depths on the shaft to be used for anchoring. There must also be land suitable for the depth of anchoring.

Before the treatment there must be:

- Preliminary visual inspection establishing the condition of back-fill of works.
- Gas measurements and piezometric measurements
- Geological and geotechnical profile of the edges of the shaft (studies already performed or specific survey) (drilling pressiometric cores) to establish depth of the firm land.
- Documentary search: cross section or plan of the mine-head, nearby infrastructure, technical or shallow tunnels, assessment of potential gas emissions

There is no maintenance but this treatment is not suited to preserving protected species.

Retention of the cap, the overlaying back-fill, surface overloads and any decoring is guaranteed and withstood by the structure being supported in the tunnels, conduits or service areas, or by using excess widths in the wall.

Closure may be achieved according to two principles: Anchoring to the service area: constitution of barriers to limit the flow of concrete to a predefined length; Anchoring to the shaft wall: this technique requires extracting the shaft lining to the desired level, temporary consolidation (injection of concrete, grill, bolts) at the ring of lining located above the location of the future anchored cap. The last operation allows supporting the lining, of which the base must be excavated. Then the enclosing rock is hollowed out to house the anchored cap.

The compression strength of the concrete is not the only factor to consider, however, for proficient long-term resistance against weathering C25/30 (standard EN 206-1) or equivalent should be used. It is also recommended that the concrete also adheres to sufficient resistance to chemical degradation (e.g. from ARD), and as such Standards: EN P18-201, P18-011 and CCTG booklet 65 should be implemented.

The choice of back-fill material above the cap also has a major influence on the design-sizing of the latter. Landfill of varied grain size (see “back-fill” information sheet) or lean concrete can be used

The choice of infill material above the plug also has a major impact on its design sizing.

The most frequently-encountered complexity criteria (excluding accessibility to the mine-works) are:

- Removal of backfill if the shaft has been filled.
- Controlled backfilling, insertion of a packer or overhead planking/coffering if the shaft is empty.
- Blocking/coffering of tunnels, pipes or service areas running alongside the shaft (potential gas emissions)
- Use of special concrete or pumping if the shaft is submerged with water
- Work in the shaft: complexity/constraints of safety increase dramatically with depth
- Special measures (pumping discharge points) if the presence of water renders this necessary (mine-works emerging for a shaft at a low topographical point)
- If gas present in the shaft during works, use of plant fitted with anti-explosion systems and detection equipment for personnel
- Installation of a decompression vent if there is a residual risk of mine gas emissions

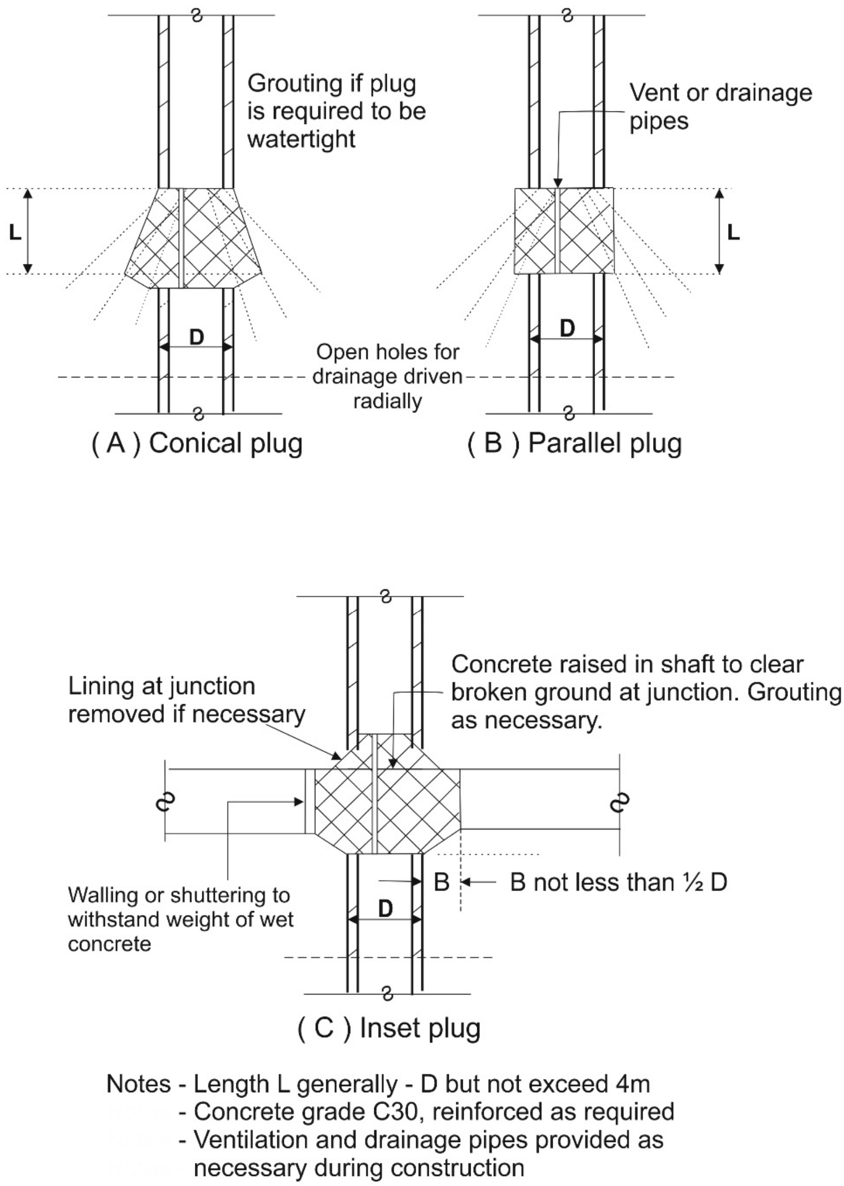


Figure 2.3: Different forms of shaft plug (NCB, 1982)

Surface Cap

Surface caps are primarily to reduce the ground movement risk when there are major challenges above or around the shaft (e.g. occupied building, road with traffic) but they also eliminate the risk of falls and physical injury.

To use a surface cap there must be resistant land within 5 m of the surface and the shaft must be accessible to vehicles. There is no associated maintenance. Surface caps are not suitable for preserving protected species.

Before the treatment there must be:

- Preliminary visual inspection establishing the condition of back-fill of works.
- Gas measurements and piezometric measurements

- Geological and geotechnical profile of the edges of the shaft (studies already performed or specific survey) (drilling pressiometric cores) to establish depth of the firm land.
- Documentary search: cross section or plan of the mine-head, nearby infrastructure, technical or shallow tunnels, assessment of potential gas emissions

A surface cap works by clearing the top of the shaft and then concreting. The surface cap, frequently known as the “champagne cork” is design-sized so that its support on the sound solid material enables it to bear its own weight, that of surface overloads and any effects of sudden decoring if the shaft is back-filled.

These supports must be design-sized taking into account the reaction capacities of the supporting solid ground. In particular, the support surface must be sufficiently wide enough to avoid phenomena of stress concentration (or “corners”) which are likely to cause failure of the supporting firm land.

The installation of a surface cap requires clearing the land at the mine head, down to the depth of the firm ground over an adequate diameter.

There may be variants of this type of structure, notably when the infrastructure around the mine head is concreted to a guaranteed strength. The concept of distributing support over the firm ground, whether natural (rock) or artificial, avoiding stress concentration, must be the basic principle of design-sizing.

The choice of back-fill material above the cap also has a major influence on the design-sizing of the latter. Landfill of varied grain size (see “back-fill” information solution) or thin concrete can be used. The choice of infill material above the plug also has a major impact on its design sizing.

The most frequently-encountered complexity criteria (excluding accessibility to the mine-works) are:

- Removal of back-fill if the shaft has been filled.
- Controlled back-filling
- Insertion of a packer or overhead planking/coffering if the shaft is empty
- Blocking of pipes running alongside the shaft (potential gas emissions)
- Pumping if the shaft is submerged with water
- Special measures (pumping discharge points) if the presence of water renders this necessary (mine-works emerging for a shaft at a low topographical point)
- If gas present in the shaft during works, use of plant fitted with anti-explosion systems and detection equipment for personnel
- Installation of a decompression vent if there is a residual risk of mine gas emissions

Injection/Inclusion Techniques

The risk of ground movement when there are occupied buildings, a road with traffic or other challenges directly over or around the shaft. It is also used to remove the risk of falls.

These techniques involve injecting grout/mortar/concrete/etc. to reinforce the back-fill in the shaft and/or the surrounding land. They involve no maintenance but to install there must be vehicle and/or infrastructure access to the shaft.

Before the treatment there must be:

- Visual inspection of surroundings and encumbrances around the shaft.
- Establish the condition of back-fill of works.
- Gas measurements and piezometric measurements.
- Geological and geotechnical profile of the edges of the shaft (studies already performed or specific survey) (drilling pressiometric cores) to establish depth of the firm land.
- Nature of shaft back-fill in the event of treatment therein.
- Documentary search: nature of backfill, cross section or plan of the mine-head, nearby infrastructure, technical or shallow tunnels, assessment of potential gas emissions

Injection techniques are generally utilised in the following scenarios:

When the load-bearing rock is located at considerable depth, traditional “cap” solutions and anchoring in solid ground become technically or economically unfeasible. With reinforcement/improvement, resistant ground is created around the shaft, limiting or preventing extension of any collapse at the mine head. The back-fill in the shaft may also be consolidated to create a structure an equivalent to a cap;

When the shaft is not accessible because it is located under buildings or other superstructure preventing insertion of a traditional cap. By inclined drilling, a consolidated block is created in the shaft, ensuring it is lodged in a solid mass on the extrados of the works.

There are many injection methods, and many possible material compositions, with variable operating pressures according to whether it is wished to include material in the land, or replace the latter. The main existing techniques are **solid injection** (grout, mortar) to densify the ground at various depths, **ballasted columns** which incorporate granular alluvial/clay soil which can be bound by grout or cement, **jet-grouting** which pumped in at high pressure, (20 to 40 MPa) replaces the original soil by grout. Land-strengthening companies have frequently created their own processes, which are fairly similar to these techniques. It is also possible to insert **ridged inclusions** (of the tie-bolt type) to anchor a cap injected in the rock on the extrados of the shaft.

Treatment around the shaft

The important points concerning the choice of technique are the depth of the soil to be treated, the perimeter around the shaft to be treated (depending on the potential impact margin for hazards linked to failure of the mine-head), and the grain size of the soils (distribution of gravel, sand, alluvium, clay). This finial parameter in fact orients the choice of technique, the density of injection points and the operating pressure. If the sound bedrock is below 30 metres efficaciousness of this technique is difficult to prove.

Treatment in the shaft

The method is to create a structure inside the shaft which can withstand coring of the back-fill, either by friction (same principle as self-supporting cap) or by anchoring and shear resistance in the ground on the extrados of the shaft lining. The important points concerning the choice of technique are depth of the shaft to be treated, the grain size of back-fill present in the shaft, the nature of the lining (if this is to be drilled, to install tie-bolts), the maximum slope of test drills given the space available on the surface.

The use of these sometimes innovative techniques requires a detailed project design study.

The most frequently-encountered complexity criteria (excluding accessibility to the mine-works) are:

- Controlled back-filling, insertion of a packer or overhead planking/coffering if the shaft is empty
- Encumbrances and presence of infrastructure/buildings on and around the shaft
- Blocking of pipes running alongside the shaft (potential gas emissions) Use of special concrete if shaft or surrounding land is submerged in water
- Insertion of a decompression vent if there is a residual risk of mine gas emission

Vents

None of the above techniques solve risks associated with mine gas such as asphyxia, ignition or explosion, or exposure to ionising radiation. For these risks a vent can be used. It aims to control surface emissions of mine gas according to the anticipated flow-rate and composition and is usually done in conjunction with treatments to reduce the risk of physical injury or ground movement. Maintenance is required every 6 months

Before the treatment there must be:

- Measurements of gas (flow rate, composition) at various periods to assess the pertinence of use of this technique in mining areas where mine gas hazards are uncertain.
- Subsequently, a study is frequently necessary to estimate the safety radius around the vent, to take into account the risk of explosion, ignition, asphyxia, poisoning and exposure to ionising radiation.
- Accessibility to the shaft or mine head. Verification of configuration of the site and the possibilities of installing a safety vent, positioning the top at a sufficient height, and accessing the various vent components for upkeep and maintenance.

Given the following constraints, notably linked to maintenance and upkeep of the vent, before committing to this technique it must be established whether it is pertinent, given the potential "gas emission" risk. A study should be prepared to define the flow rate and composition of the gas since this will have a direct influence on the nature and characteristics of the vent, and the required safety radius.

The design-sizing of the vent (a diameter which may vary from 50 to 150 mm, a height which may vary from 3 metres to some 10 metres) will depend on the anticipated gas flow rate from the works, according to the volumes of mining voids, height of the pump outlets, flow rate of the gas and its composition. The flow rate will be higher during periods of low atmospheric pressure for so-called former "closed" mines (base-surface links principally composed of blocked shafts/tunnels).

The design-sizing must take into account the potential chemical effects of gas which may be present (methane, gas low in oxygen, carbon dioxide, hydrogen sulphide, nitrogen oxide, radon etc.): Accidental ignition of fire-damp (creation of a torch-type fire is possible if the outgoing foul air incorporates flammable gases in certain proportions, either directly on leaving the vent or following their dilution in air and contact with a source of ignition), the thermal effects linked to an unconfined gas explosion; the role of the wind must be taken into account for orientation and length of the smoke plume; Poisoning or asphyxia (gas more or less toxic); Corrosion of the structure; Accidental risks (ignition, explosion, intoxication, asphyxia etc.) but also chronic risks (exposure to ionising radiation linked to the presence of radon). Sufficient distancing of dwellings or adequate height to ensure dilution of gasses must be ensured, depending on the configuration.

The vent is made of several components: non-return valve, flame arrester, device for gas measurement (content and flow rate), ¼ turn valve to close the outlet at the base for maintenance and upkeep.

One vent which operates successfully (in the case of a closed system, and while the mining voids represent an adequate volume) presenting differential pressure variations opposite to variations in barometric pressure.

The construction of a fence with an access door may be necessary if significant flow rate of foul gas in anticipated and if the height of the flame requires extending the safety radius, to protect from risks of ignition, explosion, intoxication, asphyxia and exposure to ionising radiation.

The most frequently-encountered complexity criteria (excluding accessibility to the mine-works) are:

- Encumbrances at the site requiring special provisions
- Some shaft vents may be remote from the works being treated (lack of space on the surface, etc.), and the pipe linking the shaft and the vent is then underground. The route of the pipe must be traced and mapped from its start (mine head in general) up to the vent in the same way as traditional pipes (DICT). Prefer pipes and equipment with the least possible loss of load (a non-return valve prevents entry of atmospheric air but requires over-pressuring up-stream to allow the gas to exit)
- Increased frequency of surveillance and maintenance in sensitive areas: verification of satisfactory functioning of the vent (soiling, oxidation of ferrous components etc.) non-degradation, access and integrity of the fence and information provided

Geo-synthetic membranes

Geo-synthetic membranes are used to combat the risk of ground movement associated with the presence of a shallow, improperly filled shaft. It is not recommended for open shafts. This technique reduces the consequence of ground movements without treating the cause and there is little feedback on its use.

To use this treatment the shaft must be filled, the area around the shaft needs to be accessible to site plant and there needs to be level land which can be compacted. The maintenance activities required are:

- Tests under the norm EN 13251
- Frequent visual inspection of the slope (e.g. biannually)
- Periodical re-working of earthworks including the replacement of geo-composites (e.g. every 10 years)

Geo-synthetics can be classified in three major categories: Geo-grills, which have a discontinuous flat structure, of which the varied mesh is adapted to the terrain. These structures, generally made in steel or PEHD, are selected depending on their shearing resistance and tensile strength. Geo-textiles, woven or non-woven, have a continuous flat structure. Of varied chemical composition, their main purpose is to filter, drain or resist puncture by equipment. Tensile strength is not their main function but the denser types can cope with some slopes and the tensile stress generated. They are frequently used in association with a geo-grill or a geo-membrane. Geo-membranes also have a continuous flat structure, but their role is to limit insofar as possible, the passage of liquids. They are used to render the works impermeable. Excluding specific use, geo-membranes are not immediately adapted to treating the surface of mine-works.

The Comité Français des Géosynthétiques (http://www.cfg.asso.fr) has published numerous guides facilitating the choice of geo-synthetics depending on the desired purpose: drainage, filtering, anti-puncture, resistance to tensile load, impermeability.

The manufacturer of the geotextile will have to accomplish what is specified regarding to the marked CE (Directive 89/106/CEE).The characteristics of the material will have to allow it to be resistant (without suffering tear when putting the overburden over it). For these purposes, the material will have these characteristics: The longitudinal tensile strength won't be inferior to 21.1 KN/m. The transversal tensile strength won't be inferior to 24.8 KN/m. The longitudinal elongation in minimum breakage will be of 60 %. The transversal elongation in minimum breakage will be of 60 %. The minimum elastic indentation will be of 3930 N. The maximum dynamic perforation will be of 10 mm. The minimum permeability perpendicular to the plane will be of 31 l/m2/s.

With regard to treating mine shafts, it is important first to identify the anticipated impact on the surface of remobilising the back-fill in a shaft, extending the affected zone and the maximum tensile stress this may generate. A specific study, possibly with the support of modelling is deemed extremely important for the choice of the correct category of geo-synthetic to use.

Constructive techniques:

- The geo-synthetics will be extended over a flat surface, previously shaped and free of sharp elements. The overlaps between layers won't be inferior to 50 cm, excepting that the joints between them are made by sawing or welding, in which case the overlap could be reduced to 30 cm.
- The infilling of the upper layer, generally of granular material, will be made very carefully in order not to damage the geosynthetic, not allowing the circulation of trucks over the textile. The first layer to extend, of thickness of 40 cm, will not content elements of superior size of 200 mm.
- The surface in which the geosynthetic will be extended will be clean and free of elements that can harm the geosynthetic.
- The extension of the upper layer will be in that way so that the machinery for the extension and compactation will never circulate over the surface of the geosynthetic.
- The first layer of material will be at least of 40 cm and the maximum size of the arid won't be bigger of 200 mm.
- It has to be adherent enough to the surface in order to absorb the impacts from the environment.

- The way of placing the net and its size is very important because it will determine the capacity of the solution.

2.1.2 GAS HAZARD MITIGATION

Carbon dioxide and methane are commonly found in coal mines. Hydrogen sulphide is also known to occur but is significantly less common.

Table 2: Mine gas compositions and hazards.

	Carbon Dioixde (with Nitrogen)	Methane	Hydrogen Sulphide
Dangerous characterisic	• Oxgen depleted	• Combustible and explosive • Oxgen depleted	• Poisonous
Hazard	• Asphyxiation	• Fire and explosions • Asphyxiation	• Poisoning

Unmined portions of the coal seam can release gas after mining has ceased. The gas can accumulate within natural porosity in the strata, in addition to mining voids and voids within the backfill material. Gas migration to the surface can be accelerated via a range of mechanisms. The most common reason is the rising water level within a mine after pumping has ceased, but an increase in the reservoir because of continued gas release, changes in barometric pressure and natural drafts can also cause migration. Methane is particularly prone to rising to the surface as it is light. At the surface gas can escape as a sudden concentration or it can build up in confined, unventilated spaces like cellars, building or even low lying hollows.

The gas can migrate to the surface through four pathways (Pokryszka et al, 2005)

1. Mine-surface links, e.g. un- or insufficiently sealed shafts and adits
2. Fractures and faults
3. Permeable strata (generally if cover is over 200 m thick gas can only migrate diffusely)
4. Dissolved in water drainage (least important)

Filling shafts reduces the possibility of gas escaping, especially is the cap uses a gypsum/cement/other suitable material seal, however as mentioned above voids in the fill itself can hold gas accumulations (NCB, 1982)

Gas Treatment Methods

There are both active and passive methods of treating mine gas. Gas capture is the active treatment options. A vacuum is applied to the mine to prevent the gas from reaching the surface. This is typically highly complex and expensive and therefore only generally used in acutely problematic mines.

The passive option is to create preferable pathways for the gas to vent at specific localities at the surface which are fitted with flame arrestors and lightning conductors (NCB, 1982). Such conduits can include vent pipes in adits/shafts or purposely drilled boreholes (Pokryszka et al, 2005).

If for any reason such methods cannot be (or are insufficiently) applied then redevelopment of the site is often not advisable until stable (and acceptably low) gas emissions occur, which is often after the re-flooding of the mine has occurred. Any infrastructure built should be designed to prevent gas entry and accumulation (Pokryszka et al, 2005). e.g. the use of gas sumps beneath buildings.

2.1.3 WASTE ROCK

Waste rock can be used as backfill, but backfill is not always desirable if there is the possibility of recommencing an operation in the future. Waste rock left on the surface is often aesthetically damaging, can inhibit alternative land uses, and is hazardous due to the potential for landslides, surface and groundwater contamination, and dust emissions.

Waste rock can often be used as aggregate and construction material. To maximise the efficacy of this process such waste rock should be sorted by material and environmental properties as it is being produced. If rock cannot be reused it must be reused in another capacity or disposed of appropriately.

Capping is a commonly applied approach to remediate waste rock for the following reasons:

- It limits erosion and dust emissions
- It keeps the waste chemically stable (this is particularly important for sulphide-bearing waste rock which can therefore produce ARD)
- It can enable the retention of water and soil mass which in turn will encourage the establishment of plant species and organisms
- If done appropriately it can enhance the aesthetic image of the site

Waste can be left uncovered if it will not be a health and/or safety hazard to humans or the environment. Vegetation should be established or water controlled to prevent long term erosion. If the waste is not a health hazard to humans or wildlife it can be left uncovered. It will still need to be landscaped to ensure slope stability and cope with erosion.

If the waste is a risk to groundwater, surface water, wildlife or human health it should be covered. Covers can be ‘dry’ or ‘wet’.

Oxygen diffusion rates are much lower in water than in air making **water covers** good for preventing oxygen infiltration into acid producing rock waste/tailings. This involves having an impoundment with water covering the waste. These are also called ‘wet covers’ (Heikkinen et al, 2008).

For a water cover to be practical there must be enough water available to ensure the stability of the water table and water chemistry. Deeper covers reduce the oxygen diffusion the best. There also must be enough water depth so that wave action cannot disturb the tailings. Using a water cover does require ensuring the long term stability of the impoundment and water supply, and the impoundment must have an outflow channel that can manage extreme flood events (Heikkinen et al, 2008).

Having a natural stream provide the inflow to the impoundment can improve the barrier by depositing extra sediment, as well as helping to restore an ecosystem by introducing local biota, along with nutrients (Heikkinen et al, 2008)

Water infiltration, dust and oxygen diffusion can be prevented using a dry layer of overburden. A **dry cover** can also reduce visual impact and encourage plant growth (Heikkinen et al, 2008)

Prior to covering tailings should be consolidated and dewatered – a temporary covering may be needed during this time to prevent dust ablation. Excessive acid production can be mitigated by adding lime, crushed limestone or pulverised fuel ash before covering.

An impermeable cover, preventing oxygen and water infiltration, can be made by spreading a sealing layer (e.g. compacted impervious clay) and then a cover layer. The cover layer protects the sealing layer from erosion and desiccation, and reduces the interaction with humans and other wildlife. The dual layers also impede upward capillary flow and help retain metal complexes transported in pore water (Heikkinen et al, 2008).

If water does not need to be prevented from infiltrating the cover material can spread without compaction or consolidation.

These methods can also be used for tailings.

2.1.4 Water Treatment

Any AMD/ARD (which coal mines are prone to producing) or water that is of a different composition to the natural water in the area needs to be treated before being discharged into local water courses. Untreated minewater pollution can reduce biodiversity along a watercourse, especially reducing fish and invertebrate populations. Damage to a river population will also effect birds and mammals which feed on river species (Coal Authority, 2005**)**. Treatment can be active, passive or a combination of both.

Generally passive methods involve have fewer ongoing maintenance costs, but take up larger land areas because they need longer retention times to treat the water (Kleinmann et al, 1998). However, some passive treatments serve additional purposes. The construction of wetlands can create a new habitat for birds, increasing biodiversity, and can be amenity land for the local population (Coal Authority, 2008)

The typical active method is to add chemical reagents to increase pH and precipitate metals out of solution. The sludge that this produces needs to be separated and disposed of. This has high operating costs. (Johnson & Hallberg, 2005)

There is also an active biological method called **sulfidogenic bioreactors**, the waters alkalinity is increased by biogenically produced hydrogen sulphide and metals are precipitated out as sulphides. This system is more controllable and predictable than a passive biological system. It can also allow heavy metals to be selectively recovered and can reduce the sulphate concentration. This process does occur in passive biological systems but it is more efficient in these active systems (Geller & Schultze, 2013)

There are many different types of passive biological methods to treat mine water.

If the water which needs to be treated does not have significant amounts of ferric iron or aluminium it may be able to be treated with just an **anoxic limestone drain** (ADL), which are cheaper than wetland systems. The water runs through an air tight anoxic limestone gravel bed to raise the pH. The anoxia prevents ferric hydroxide precipitating and armouring the gravel which reduces the ability of the limestone to raise the pH (Johnson & Hallberg, 2005; Geller & Schultze, 2013).

ADLs are often used in combination with wetlands, the ADL reduces the alkalinity and the wetland captures the precipitated iron (Johnson & Hallberg, 2005; Geller & Schultze, 2013).

Aerobic wetlands oxidise ferrous iron to ferric iron

$$4Fe^{2+} + O_2 + 4H^+ \Rightarrow 4Fe^{3+} + 2H_2O$$

and hydrolyse ferric iron which produces acid.

$$4Fe^{3+} + 12H_2O \ \Rightarrow 4Fe(OH)_3 + 12H^+$$

Therefore, water to be treated using an aerobic wetland should be alkaline.

Aerobic wetlands should be shallow to maintain an oxidising environment and contain aquatic plants. The plant serve several functions, they slow down water flow, provide surface area for metal precipitation and trap the ferric iron that precipitates out (Johnson & Hallberg, 2005).

Arsenic is also removed by adsorbing onto positive ferric iron colloids. Some arsenic is probably also removed by thiomonas bacteria which oxidise arsenic (III), removing it from the water (Johnson & Hallberg, 2005).

Anaerobic wetlands, also known a **compost bioreactors** as they can be underground and without aquatic plants, can be used for acidic, metal-rich waters. The process uses microbially catalysed reactions within an organic compost which generate net alkalinity and biogenic sulphate (Johnson & Hallberg, 2005). The compost is made of biodegradable material, such as cow manure, and less biodegradable material, such as straw and sawdust (Geller & Schultze, 2013).

Composite aerobic and anaerobic wetlands combine the two methods above. Water first oxidises and precipitates out iron hydroxide in a pond before travelling through microbial cells with an aquatic plant covering. The microbial cells raise the pH and remove more metals (Kalin & Chaves, 2003)

Permeable reactive barriers channel the contaminated water through a trench containing organic material (and sometimes limestone) in which reducing microbial activity raises the alkalinity and remove metals as sulphide, hydroxides and carbonates (Johnson & Hallberg, 2005).

Iron-oxidising bioreactors use iron-oxidising prokaryotes to accelerate iron oxidation in acidic waters (Johnson & Hallberg, 2005).

2.2 ENVIRONMENTAL RISKS ASSOCIATED WITH MINE CLOSURE

Failing to close a mine properly can have dangerous and expensive consequences which are detailed here.

Underground mining will impact the surface and landscape through extraction, processing plants, waste heaps and low-grade stockpiles, tailings lagoons and settlement ponds. The greatest disturbance will be from subsidence. Subsidence could cause flooding or drainage of the soil. Near-surface subsidence is particularly hazardous for buildings other surface structures.

Water in a mine is normally controlled by pumping to keep the mine dry. Once closed and pumping turned off, mine workings will start to fill up with groundwater and the levels will rise until it reaches the surface or discharges into overlying aquifers which can takes many months or years.

After mechanical ventilation ceases in a coal mine the natural air flow will depend on the barometric pressure, the variation of temperature and humidity, the mine depth and changes taking place within the mine, such as rising water levels or collapsing workings. Methane, being lighter than air, tends to rise, and significant volumes can continue to be emitted through interconnections, to the surface for some time after working ceases. This gas can be flammable (in open spaces) or explosive (in confined spaces) at concentrations between 5% and 15% by volume in air. Potential radon emissions from unsealed workings can be hazardous owing to their carcinogenic nature.

Many of these key environmental hazards in coal mines are interrelated as shown in the figure below.

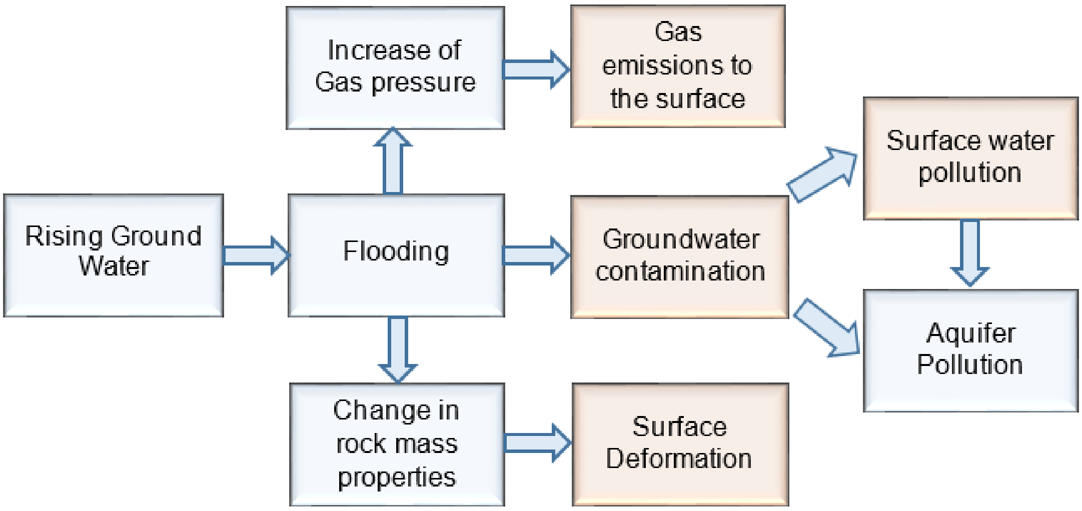


Figure 2.4 The interrelationship between coal mine closure hazards

2.2.1 *SHAFTS AND SINKHOLES*

Abandoned mine shafts can suddenly and unexpectedly collapse. The potential hazards presented by abandoned shafts include the following (Donnelly, 2015)

- Collapse or movement of the ground. This may occur suddenly, or gradually;
- The discharge of acid or ochrous minewaters, which can result in pollution of water courses and aquifers;
- Flooding of basements, building and structural foundations;
- Emission of mine gases; and
- Accidental entry: injury or death is almost inevitable following a fall down a shaft. Flooded shafts compound the risk with the added danger of drowning, suffocation or poisoning by gas; collapse of the shaft is also possible, once disturbed.

The previously mentioned MISSTER project (Lecomte, et al., 2012; Salmon, et al., 2015) identified 7 different causes as to why shafts have collapsed. There are some very subtle differences between some of these causes which are summarised below.

Figure 2.5: Collapse of Shaft in Lancashire, UK (Lecomte et al 2012)

1) Collapse of an infilled shaft

The shaft fill material is abruptly remobilised downward, rushing into the old workings causing a collapse of the surface (if no structure or protection was installed at the head of the shaft). Collapse of the shaft filling material occurs generally after a slow degradation of the conditions of the filling material (E.g. due to rising water after the cessation of pumping). Other examples include the partial collapse of shaft filling material into voids which formed during the original shaft infilling.

Case study: Shaft collapse – Wattenscheid, Germany

A void opened in a residential area of Wattenscheid, Germany, in January 2000. It was 15 m deep and had a surface area 500 m^2. The void formed over a mine shaft in the former Maria-Anna coal mine and damaged residential structures and an access road.

Figure 2.6: Sinkhole in residential development in the city of Bochum (a. (Nölkensmeier, 2000); b. (Seiler, 2016); c. (Rönsberg, 2012))

During mine closure in 1906 the shaft head frame collapsed into the shaft, damaging the shaft lining and getting stuck ~40 m below the surface. The headframe was left and the shaft then filled. The filling material had a large grain size, this and the abandoned headframe lead to large void spaces in the shaft. In total only ~ 2,200 m^3 of filling material was put into a 13,000 m^3 shaft. Safeguarding works took place in 1989, however they only acted on the top 35 m of the shaft.

Over time water exposure and other processes rotted the wooden shaft lining that had been ripped out of place by the falling head shaft and was lodged in the shaft with the headframe. The void moved towards the surface and there were more rock and soil falls. This continued movement formed the sinkhole and a series of preceding earthquakes.

In order to safeguard the damaged area, almost 7,500 m^3 of concrete were pumped in.

2) Failure of the shaft head

Many shafts have been closed in the past using standards which wouldn't be acceptable if they were applied today. For example, shafts were closed by a single on-surface or near-surface wooden platform, eventually completed to surface by filling material on the shaft head but leaving the whole shaft column empty. Such structures could fail due to degradation over time due to the effects of moisture. Concrete slabs have also been used as a shaft head, but these can break when they are subjected to excessive loads, or when surface ground materials on which they rest fail. Figure 2.7 shows such an example from the West Midlands, UK, where a 3m diameter shaft, 144 m deep failed in 2000 in a carpark due to the weight of a motor vehicle.

Figure 2.7: Shaft collapse in a car park.

Occasionally, a collapse may occur in the vicinity of a shaft due to developments and activities applied on surface. Several causes are likely to lead to these instabilities of the ground level. For example, an overload on the surface or in the immediate surroundings of the shaft head, such as storage of exploited material, heavy vehicles or construction. Vibrations generated by explosions or blasting near the shaft head or by intense circulation of very heavy vehicles can also cause instability.

3) Failure of the shaft lining

The most frequent failures of shaft linings result from a decrease of its resistance or from an increase of the surrounding pressure of surrounding grounds. When the strength of the lining is exceeded, the lining (bricks, stone blocks, concrete, cast iron and steel) deforms and eventually breaks. This results in a collapse in the shaft along with part of the surrounding ground.

The decrease of the mechanical properties of a lining material with time is an inevitable phenomenon resulting from the progressive ageing of the constituent materials. Shaft backfilling operations made without sufficient precautions may also damage linings, and so will stones/blocks dumped from the surface that fall several hundred meters and can sometimes damage sections of the lining.

An example of such a failure, albeit for an operating mine, is that of Shaft No 2 at Barony Colliery in Ayrshire, UK (Lecomte et al, 2012) where the wood lining failed following deterioration that may have been caused by contact with upcast high of high humidity. This shaft was originally a downcast shaft until a redesign and recommissioning of the ventilation system.

Figure 2.8: Collapse of Barony Colliery No 2 Shaft Lining (Lecomte et al, 2012)

4) Failure of stoppings located into the shaft galleries

Mine workings and tunnels connected to shafts may have been closed before the shaft was backfilled in order to avoid spreading of the backfilling material into those tunnels. These structures generally consist of walls in hollow blocks, metal dams or concrete plugs. A rupture of this deep closure structure can occur allowing the filling material to spread into the tunnels, resulting in a collapse of the material in the shaft.

5) Effects of Water

Inflowing water, either due to the water level rising, or due to infiltration because of the weather, can cause failure of the filling material. The additional water within the column of the shaft adds weight and may reduce the fill strength due to pore pressure generation, disturbing the equilibrium state within the column and generating failure of the shaft lining.

Lecomte (2012) cited a shaft located in Tirphil, UK, collapsed in 2010. A 4 m deep hole formed in the road, 4-5 m in diameter, brickwork was visible and water was entering the hole from a culvert. Due to water ingress from the culvert the collapse grew in size, the following morning was approximately 10 m in diameter, 15 m deep and filled with water to approximately 4 m from road level.

Figure 2.9: Collapse of Shaft at Tirphil.

Coal Authority data showed that the collapse is on the position of a mine entry. Shallow recorded mining exists beneath the site approximately 22 m below road level and deep mining between 370 m and 480 m. The shaft is connected to an adit which is described as “the lowest free drainage for the Brithdir Seam in the Rhymney Valley” on abandonment plan 6467.

6) Rupture due to particular geological formations

The presence of particular geological formations, such as soluble horizons (gypsum / salt) or soil seams lacking cohesion which are susceptible to flow (sand for example) may induce the creation of voids behind the lining. This void may destabilize the lining of the shaft and induce its collapse.

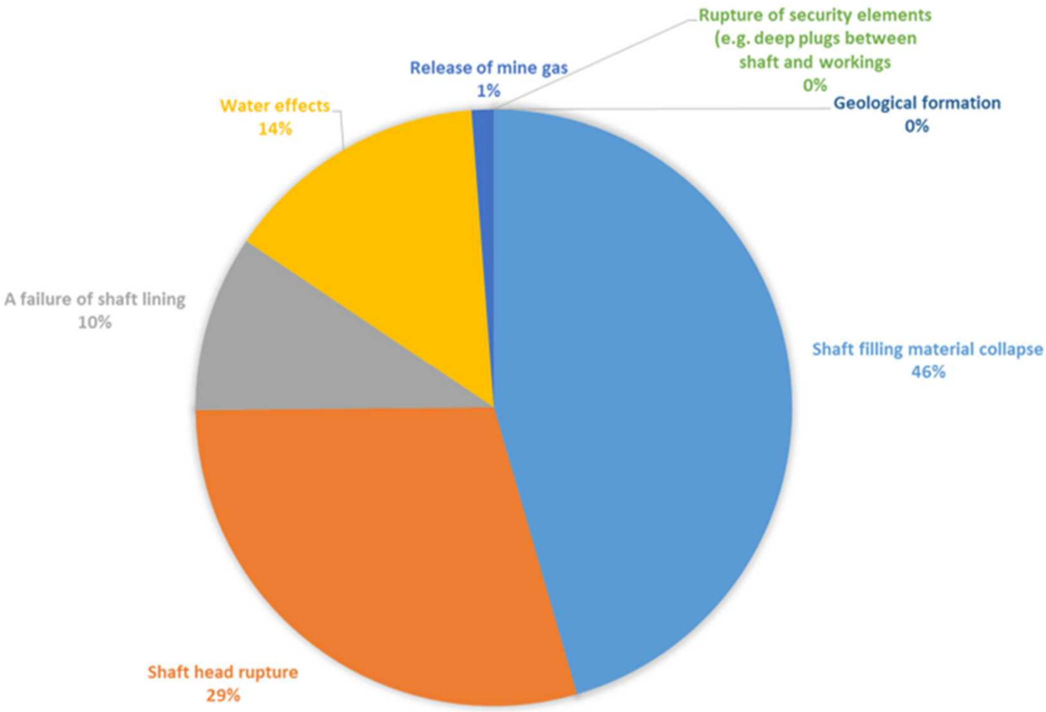
7) Subsidence due to remobilisation of filling material or surface development

Occasionally, a slow and progressive remobilisation of the surface layer (shaft backfilling material and low cohesive ground material) occurs in the vicinity of a mining opening. Settlements occur within the backfilling materials as a result of compaction. Under the effect of outside disturbances (on-surface overload, vibratory stress) or due to a remobilisation of filling materials, grounds or backfill material can settle and induce movements of low amplitude (generally the maximum amplitude is a few decimetres).The results are mainly surface differential settlement that may affect buildings and infrastructure.

The MISSTER project (Salmon et al, 2015) looked in detail at 322 shaft collapse incidents in the UK, and found 143 with clear information regarding the failure mode. These 143 cases were reviewed and organised according to the main failure scenarios previously established, namely:

1. Shaft filling material collapse
2. Shaft head rupture
3. A failure of shaft lining
4. Rupture of security elements (e.g. deep plugs between shaft and workings)
5. Water effects
6. Geological formation
7. Release of mine gas

The distributions of the cases at each failure scenario are shown in the figure below (Salmon et al, 2015). It is recognized that the selection of failure scenario is subjective and that several scenarios may apply to a single failure incident. The data shown in the figure should therefore be interpreted with some consideration of these factors.



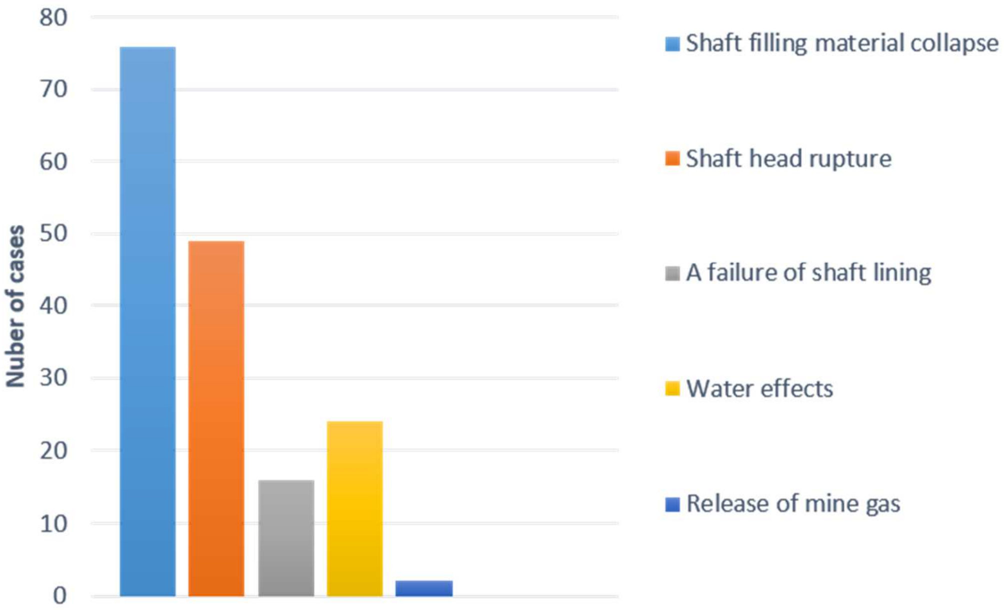


Figure 2.10: Distribution of Shaft Failure Scenarios – MISSTER

What this analysis does show, however, is the important role played by backfilling material, lining and the strata around the shaft head in the stability of shafts.

Case Study: Gosforth, Newcastle upon Tyne

In November 2015 a void opened up in a housing estate in Gosford. The mine shaft, known as Coxlodge Colliery Jubilee Shaft, was operational during the 1820s and is nearly 200 years old. The mine was recorded as being closed in 1891, but subsequent investigations showed that the shaft was left open after this time to help ventilate other mine workings in the area (Coal Authority, 2016).

Figure 2.11: Initial collapse of Gosforth Shaft

Following extensive ground investigation a hexagonal, steel reinforced concrete slab to cover the mine shaft was constructed which now sits two metres below the ground.

Figure 2.12: Construction of the hexagonal, steel reinforced concrete slap

Figure 2.13: Completed remedial works in Gosforth

Under the slab 35 m^3 of resin grout was injected into the shaft to ensure the area was completely stabilised.

As this sinkhole occurred at the location of a known shaft, the failure is understood to be caused by the deterioration of the shaft cap over time. This collapse was brought on by the recent heavy rainfall.

2.2.2 GROUND MOVEMENT

Surface subsidence as covered in this section, refers to subsidence that occurs as a result of longwall mining. In longwall mining, as a coal face advances or retreats (depending on the methodology,) the immediate roof behind the supports breaks and falls into the extracted cavity. Whilst this collapsed material only extends some 6-10 m above the worked seam, higher levels of strata will tend to sag into a fairly regular trough shaped curve which develops up to the surface and extends with the working coal face. The area of the surface affected is greater than the worked area of the seam.

Figure 2.14: Tilt Subsidence due to longwall mining (Whittaker & Reddish, 1989)

An empirical method for the shape of the subsidence trough is contained within the “Subsidence Engineers Handbook” (NCB, 1975) based on observations at around 200 sites in several coalfields around the UK collated between 1950-65 (Whittaker & Reddish, 1989) It has been extensively used throughout the UK as a means of assessing the anticipated response of the surface to underground extraction. It has also been employed widely in other countries and is frequently used as a standard basis upon which to compare local subsidence observations.

It is recognised that the time factor aspects of mining subsidence indicates that subsidence development is directly associated with the rate of extraction within the area of influence of the surface (Whittaker & Reddish, 1989). The majority of measureable subsidence will occur within about 12 months of working. However some residual subsidence, amounting to about 5 % of the total (NCB, 1975) may continue to occur over the following 6-12 months. There have been a few isolated cases where residual subsidence has exceeded this length of time and can be in the order of 4-6 years (Whittaker & Reddish, 1989). Donnelly (2015) states that residual subsidence rarely exceeds 10 % of the total, but in some cases has ranged from 8-45 % of the total and continued for up to 11 years after operations cease.

Mine closure can also be related to upward ground movement as the flooding of a mine can result in surface uplift. Why this happens is not fully understood. One hypothesis put forward by Pottgens (1985) is that rock mass that has been disturbed by underground exploitation has a higher porosity and permeability than an intact rock mass. An increase in water levels within the mine leads to increased pore pressure in the exploited zone and causes expansion due to the decreases in the normal stress. Fenk (1997) suggested that the increase in the mine water level leads to an elastic expansion of the heavily fractured rock strata located above the mined deposits.

The resulting continuous deformation (uplift) is not a big threat in itself. According to Pöttgens (1985), the maximum uplift of the area can range approx. from 2 to 5% of the maximum subsidence assuming the water level reaches the ground surface. This magnitude of displacement does not usually lead to the formation of new damage, especially not significant damage. However, this cannot be applied to the areas where there are large tectonic faults in the structure of the rock mass. The measurement results obtained so far have shown that there is a possibility of not only continuous uplift, but also discontinuous uplift around fault outcrops, i.e. fault acts as a barrier, one side doesn't experience uplift.

Case study: Surface uplift around the Sophia-Jacoba mine, Wassenberg, Germany

In 1997 coal mining ceased at the Sophia-Jacoba mine in Wassenberg, Germany. The area had been mined since 1914 and between 1953 and 1997 there had been 3 metres of subsidence. After 1997 water was allowed to flood the workings which caused uplift. From 1997 to 2000 the maximum uplift was between 10 and 20 mm per year. However, from the end of 2001 to May 2003 the uplift was between 30 to 40 mm per year, resulting in damage to 120 buildings, 9 of which had to be demolished. This increase in uplift rate occurred when the water level in the mine reached the overburden (Cuenca & Hanssen, 2008).

Figure 2.15: The building qualified for the total damage as a result of an irregular uplift of the ground surface

Figure 2.16: The damage to the local road located between the villages of Vogelsang and Luchtenberg.

Figure 2.17: The damage to a building annexe in Wessenberg.

2.2.3 GAS EMISSIONS

Gas emissions from closed and abandoned coal mines can take one of two forms:

1. Methane (also referred to as "firedamp"). This is always associated with coal and coal mining and is explosive when mixed with air between 5-15 %.
2. Carbon Dioxide (also referred to as "blackdamp" or "stythe"). In essence this is oxygen deficient air (it is composed of nitrogen and higher than normal levels of CO_2). It is colourless, odourless and tasteless and is normally heavier than air.

Methane emissions from closed and abandoned mines are characterised by a high rate of release immediately following closure, then falling to much lower levels over a period of between 8-10 years (WSP, 2011). Surface escapes of methane, commonly accompanied by combustion are comparatively well known in most coalfields (Young & Lawrence, 2016).

Under certain situations CO_2 can migrate to the surface. In conditions of good ventilation it will dissipate into the atmosphere. However, if this ventilation is restricted, surface accumulations may reach dangerous concentrations. Being heavier than air it may accumulate in cellars and trenches and may enter buildings through foundations, pipe ducts or in some instances directly through the ground (Young & Lawrence, 2016).

There have been some tragic instances associated with surface emissions CO_2 (Young & Lawrence, 2016).

- In April, 1995 a pensioner who was passing through a factory on his way to feed a pony died from asphyxiation. The factory was on an old colliery site and CO_2 issuing from the old drift was the cause of the fatality. A dewatering scheme operated at an adjacent opencast site may have lowered water levels in the old workings sufficiently for trapped gas to find an exit to this old drift.
- A man and his dog were asphyxiated by CO_2 at his workshop in Widdrington, Northumberland in 1995. Other family members were overcome by the gas but were successfully revived.
- A man died in a trench in Barnsley, UK, in 1998 when a trench filled with CO_2 from nearby old workings.
- In 1992 the Jakub I shaft of the Zárubek mine in the Czech Republic was closed. It was filled with a mixture of crushed bricks, slag and waste rock from treated coal and then sealed with pulverised fuel ash. Access points to the shaft along its 643.5 m depth were closed off, however material in the shaft shifted around 490 m down and uncovered unsealed areas, containing large amounts of gas. This resulted in the uncontrolled release of gas to the surface.

Shallow abandoned mine workings and old shafts and drifts are the common factors in most mine gas incidents. Shafts and drifts not only allow the escape of mine case to or from near the surface but also permit upward migration from deeper seams to shallow ones. Even where shafts are filled there can be a risk of gas coming to the surface. Shaft fill may be permeable, particularly if it consists of surface debris dropped down the shaft. The annulus of the shaft outside the lining may be open and in some cases gas can permeate through strata.

There are several ways in which gas emissions from closed and abandoned mines may be created at the surface. These are as follows (after Robinson, 2000).

Cessation of Ventilation at a Mine

After mine closure, gas will continue to be released from the workings and surrounding strata. This can last for years if the mine has suffered from high emissions during its working life. These gases reach the shafts and then rise to the surface some months after the ventilation fans have stopped. They may also find their way to surface via the overlying strata if they are permeable or fractured and the workings are shallow.

Barometric Changes

When a mine is sealed the residual pressure underground remains constant. However, since the atmospheric pressure at the surface rises and falls, creating a pressure differential between the sealed workings and the surface. If connections are present and atmospheric pressure is lower than underground, gas will flow to the surface, and vice-versa. Small changes in atmospheric pressure will result in small flow rates whilst large changes will result in large concentrations of gas being pushed quickly to surface.

Rising Water Levels

Rising water levels caused by cessation of pumping results in a change of hydrostatic head and a reduction of storage volume underground as workings become flooded, forcing gas to the surface. However, when the water levels are restored to their original levels and the workings flood completely this problem reduces.

Fires Underground

In rare circumstances CO emanating from an underground source, such as a fire can become a hazard at the surface. Here, the heat produced can be sufficient to propel CO to the surface via fissures in the strata above a shallow coal seam.

Case study: Fatal accident in Bielszowice coal mine, Poland

On 3rd January 2000 an endogenic fire began in the Bielszowice coal mine. The fire began in goad which the main drift went through.

An employee went to check the methane drainage pipeline. The team leader went in the same direction to find material to build a wooden bulkhead. As the team leader walked along the main roadway they saw the employee lying on the floor. The team leader went to get the rescue team. The team initially entered the workings without equipment, however when a team member lost consciousness they had to retreat. A new team equipped with breathing apparatus transported the victim out of the area, where a doctor pronounced him dead. The team leader was diagnosed with acute carbon monoxide poisoning. The rest of the team did not show clinical symptoms, but they did present with signs of exposure. Durofoam and power plant ash dust were used to extinguish the flames.

Methane Emissions Data

In the UK, 96.6% of abandoned mine methane emissions arise from deep mines (WSP, 2011) In recent years the UK Government has commissioned two studies Kershaw, 2005 & WSP, 2011 to estimate the total amount of greenhouse gas (GHG) emissions originating from closed coal mines Although the last few “large” coal mines closed at an earlier point in time than anticipated by these studies they do show a reducing trend with peak emissions in 1995 (due to the closure of a large number of mines that year due to the privatisation of the industry) (Fig. 17).

This particular study estimated emissions from 143 closed mines and 11 other mines that were scheduled to close prior to 2050. 104 of these mine were fully flooded by 2000 accounting for the initial decline, which increased to a second peak the following year due to further closures. As 79% of mine closures had occurred prior to 1990 then it is predicted that most emissions have already occurred by 2010.

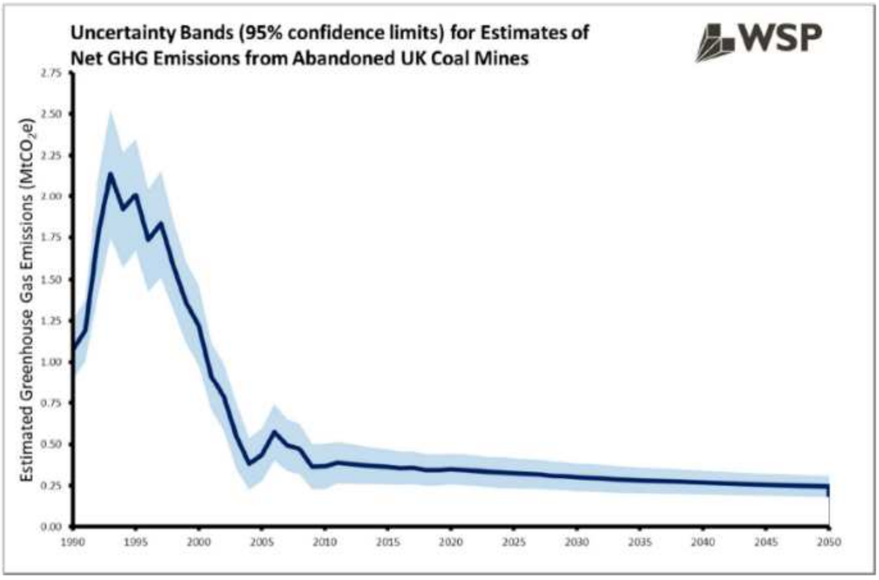


Figure 2.18: Gas Emission Estimates 1990-2050 (WSP, 2011)

Case Study: the moving of Arkwright Town, UK (Speller, 2000)

Arkwright Colliery in Derbyshire was closed in 1988 and the water drainage pumps were stopped and the access drifts were sealed. Nine months later, methane gas was found to be escaping from the underground workings and infiltrating the houses in the upper half of the nearby Arkwright village. On the night of 9 November 1988, the alert was raised and 110 people were evacuated and housed elsewhere for 15 days.

Although British Coal denied any legal responsibility for the methane emergency, they installed a gas pumping plant to vent the methane on the site of the closed colliery. The local authority placed methane meters in some houses to check for future leakage.

In the autumn of 1989, an exposed coal seam near the village ignited and burned for 4 weeks, causing fears of an underground methane explosion.

After considering several options, British Coal proposed the construction of a new village, at the cost of £15 million, on the site of the allotments and recreation area but within the original village confines. In exchange for this offer, British Coal requested planning consent to opencast 1000 acres of surrounding land over a period of 10 years to extract four million tonnes of coal. Construction was completed by 1995 when the old Arkwright Town was demolished.

Case Study: Morcinek coal mine methane gas explosion, Poland

In June 1999 there was a methane explosion in a ventilation shaft in the Morcinek coal mine, Poland. The gas had built up in the shaft which was being backfilled with gangue and exploded, injuring nine employees working in the shaft collar building.

Figure 2.19: Effects of methane explosion in backfilled shaft III. Source: JSW S.A.'

2.2.4 MINEWATER DISCHARGES

The complete closure of a mine and/or coalfield and cessation of pumping may results in the regional recovery of groundwater levels and the flooding of the mine workings. Should the mine waters reach the surface, discharges may occur which can and do result in the pollution of surface water courses and contamination of aquifer water supplies.

Other geohazards associated with rising groundwater in coalfields are (after Yu, et al., 2006):

- Landslides – rising groundwater levels cause landslides via elevation of pore water pressures;
- Ground Subsidence – water surges caused by collapsing workings may induce or renew surface subsidence;
- Seismicity – as groundwater levels rise, water may penetrate faults/joints, reduce strength and reactivate the fault;
- Gas emission (see previous section)
- Impact on structures – particular deep basements or shallow foundations;
- Mobilisation of pollutants – due to changing groundwater chemistry

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.

Minewater can cause sudden incidents, an example of this was in 2002 where a major outburst of minewater from old workings in South Yorkshire, UK washed away a section of a main road, which had to be closed for several days.

Figure 2.20: AMD Discharge

Mine water issues from closed mines also effect active mining operations. In the UK four miners were killed at Gleision Colliery in Wales when the active workings intersected adjacent old flooded workings in 2011.

Case Study: Gleision Colliery, UK

On 15 September 2011, an inrush occurred at the Gleision Mine, a small scale coal mine, in South Wales, UK. This inrush resulted from breaking into old adjacent flooded workings and resulted in four mine workers losing their lives.

A blast released a large body of water from adjacent old workings which rushed into the working stall (HSE, 2015)

Figure 2.21 shows the extent of the flooded old workings in the area (grey) along with a cautionary zone (green lines) between the current and old workings.

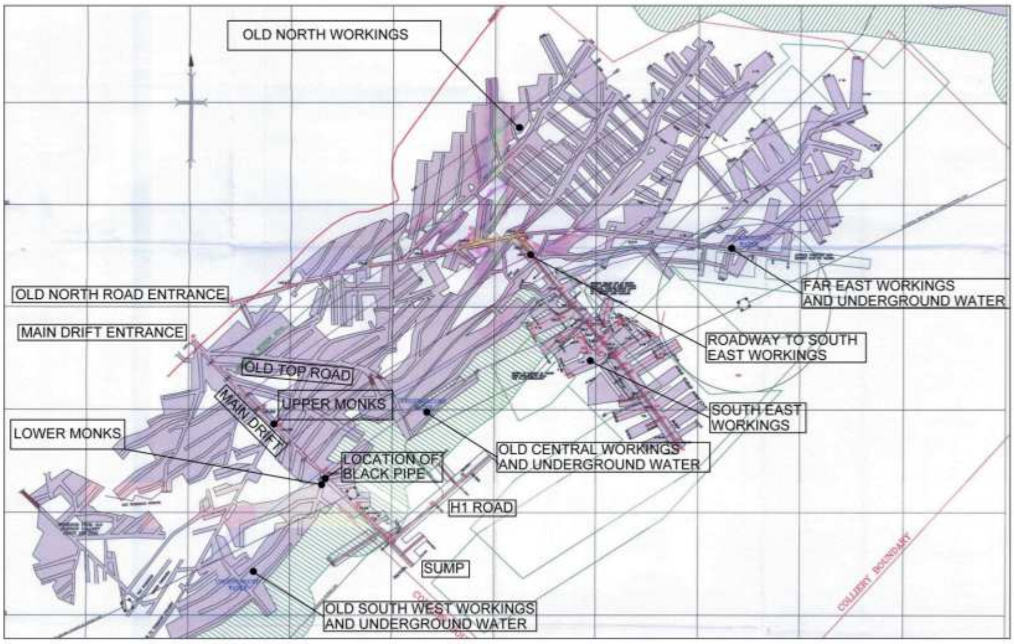


Figure 2.21: Gleision Mine Plan (HSE, 2015)

The most recent coal working were to the left hand side of the H1 roadway which are not included on the plan as the workings had started after the last update of the plan.

The inrush occurred immediately after the centre section face of a coal production area, which was approximately 7.5 m wide and 0.75 m high, was blasted with explosives breaching the remaining coal between the stall and some old workings above that were waterlogged at the time the breach occurred. This allowed somewhere between 2500 and 3000 tonnes of water, silt and stone debris to flow down the 1 in 5 gradient and through the stall in about two to three minutes at a speed of about 20 mph, which swept away everything in its path, including the roof supports and equipment (HSE, 2015).

Three of the four people within the stall were overwhelmed and lost their lives. The mine manager, who was with them, narrowly escaped death and emerged from the mine about 45–60 minutes later having escaped through old workings after the inrush had subsided. The fourth person who died was in the H1 roadway near the bottom of the stall and tried to escape but was overwhelmed by the inrush about 20 m from the bottom of the main drift. One person with him only just escaped.

A number of unknowns prevented accurate calculations of the water above the breach before the inrush and below it afterwards. However, the approximate calculations suggested the amount of water that ended up in the bottom-most parts of the mine was similar to the amount of water that could have been in the Old Central Workings above the breach before the inrush. The mine plan being used at the time was sufficiently accurate for all practical purposes. While the bottom edge of the Old Central Workings worked in the 1980s was 7 m further south than was drawn on the mine plan this was not unexpected. In any event, the use of advance drilling to locate the old workings meant that this had no bearing on the incident.

2.3 RISK CRITERIA

Risk criteria were identified and defined for every environmental risk factor considered in the project (subsidence, air quality, ground and surface water quality) in order to determine a benchmark of acceptable thresholds for the purposes of risk evaluation.

The risk criteria were based on regulatory requirements, where available, and considered stakeholders concerns with regards to human health and the environment. Regulatory requirements for subsidence, air quality, ground and surface water quality from the Czech Republic, Germany, Poland, Spain, UK and France were considered.

2.3.1 SUBSIDENCE

The classification of mining areas due to mining damage in Poland (similar to the system in Germany) is the most complete of all the countries studied. Measured deformation values were compared with the damage produced on civil structures to determine the maximum deformation values for different categories of building (Knothe, 1953; Budryk & Knothe, 1956).

This area classification (Table 3) was supplemented with the deformation over time ratio (Dżegniuk & Sroka, 1978).

Table 3: Maximum deformation limits for building categories.

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.

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 with a potential of gas explosion risk when damaged, 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, railway tracks, pipelines, blast furnaces, open hearth furnaces, coke furnaces, shafts and hoisting machines, monolith reinforced concrete industrial buildings, buildings with gantry cranes, public utility buildings (hospitals, theatres, churches with vaulted roofs), river beds and water reservoirs, main railroad stations and routes, tunnels, vaulted arch bridges, water distribution networks not protected against ground movement, large residential buildings with the length exceeding 20 m. Large cities. 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 (without gantry cranes), cold stores (non-shell), tall chimneys, smaller residential buildings (10–20 m in the horizontal projection), municipal

treatment plants, main sewage collectors, sewage pipelines, steel gas pipelines, and cable lines. Possible larger damages, without the risk of destroying the structure. 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**: sport stadiums, 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.

Buildings are classified into resistance categories using a points system based on characteristics such as length, foundation, etc as shown in Table 4. This is based on work by Grun (1998) and others.

Table 4: Assessment and classification of buildings by their damage sensitivity, after GRUN (1998)

1.	Length of object (building)								
	Length [m]	<10	10-15	16-20	21-25	26-30	31-35	36-40	>40
	Points	4	5-7	8-11	12-16	17-22	23-29	30-37	42

2.	Shape of structure		
		Simple (rectangular), connected	0
		Simple, nested	3
		Heavily nested	6
		Simply, spatially extended	6
		Nested, spatially extended	8
3.	Foundation		
		On same level, with and without basement	0
		On different level	3
		On different level partly with basement	6
		As above, with interrupted foundation levels	8
4.	Ground		
		Compressible	0
		Less compressible	4
		Incompressible	12
5.	Construction		
		Rigid	0
		Less rigid	4
		Not rigid	8
6.	Reinforcement		
		Anchorage, concrete bracing	0
		Partly reinforced	4
		Not reinforced	6
7.	Technical condition		
		Good	0
		Middle	6
		Poor	12

Points total	<20	21-27	28-36	37-47	>48
Object category	**4**	**3**	**2**	**1**	**0**

2.3.2 *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 (European level). 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.

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). For this purpose, a value of 10 mg l-1 of DOC has been used as a threshold to distinguish "clear" from "humic" waters, and the different water types are defined as follows:

- "Lowland" means less than or equal to 80 metres above mean sea level.
- "Upland" means more than 80 metres above mean sea level.
- "Low alkalinity" means a $CaCO_3$ concentration of less than 50 mg per litre.
- "High alkalinity" means a $CaCO_3$ concentration of greater than or equal to 50 mg per litre.

In general, the new proposed standards are more specific and thus appropriate to guarantee the quality of water, but they are not always tighter.

The parameters that have been identified as relevant to assess the surface water environmental impacts 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

The standards the used for surface water quality are as follows (Table 5):

Table 5: Surface water quality standards for the relevant parameters.

Parameter	Standard
pH	See Table 6
SPM (mg $l^{-1)}$	≤25
Al (µg l^{-1})	≤25
Cu	See Table 7
Zn	See Table 8
Pb (µg l^{-1})	1.2 (annual average, bioavailable concentration) 14 (maximum allowable concentration)
Ni (µg l^{-1})	4 (annual average, bioavailable concentration) 34 (maximum allowable concentration)

Table 6: pH standards.

		CLASS			
Parameter	**Water type**	**High**	**Good**	**Moderate**	**Poor**
pH recommended standards (annual mean)	Clear waters	6.60	5.95	5.44	4.89
	Humic waters	5.10	4.55	4.22	4.03

Table 7: Existing and proposed Environmental Quality Standards (EQS) for copper in surface waters based on hardness levels (WFD-UKTAG, 2007) (PNEC=predict no effect concentration)

Water type	Exposure	PNEC (µg l^{-1})	Current AA-EQS (µg l^{-1}) as dissolved Cu metal		New $EQS_{bioavailable}$ (µg l^{-1})
Fresh	Long-term	8.2	Hardness bands		
			0-50 mg l^{-1} $CaCO_3$	1	1
			50-100 mg l^{-1} $CaCO_3$	6	
			100-250 mg l^{-1} $CaCO_3$	10	
			>250 mg l^{-1} $CaCO_3$	28	
Salt	Long-term		DOC levels		
			<1 mg l^{-1}	5	3.76
			>1 mg l^{-1}		3.76 + (2.677 x ((DOC/2) – 0.5))

Table 8: Existing and proposed Environmental Quality Standards for zinc in surface waters (WFD-UKTAG, 2010)

Water type	Exposure	PNEC (µg l^{-1})	Current AA-EQS (µg l^{-1}) as Zn total		New EQS (µg l^{-1})
Fresh	Long-term	7.8	Hardness bands		10.9 bioavailable plus Ambient Background Concentration (SSD approach)
			0-50 mg l^{-1} $CaCO_3$	8	
			50-100 mg l^{-1} $CaCO_3$	50	
			100-250 mg l^{-1} $CaCO_3$	75	
			>250 mg l^{-1} $CaCO_3$	125	
					0.5 dissolved plus ABC (det approach)
Salt	Long-term			40 (dissolved)	3.4 dissolved plus ABC (SSD approach) 0.56 dissolved plus ABC (det approach)

A summary of the admissible levels of relevant pollutants in discharge water are in Table 9.

Table 9: 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	0.5

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 groundwater classification must reflect the unique features of each groundwater body.

Specific standards have been defined in different Member States (e.g. the UK and France), for substances that have been designated as hazardous. The tighter of those standards should be adopted in cases where groundwater bodies are affected.

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

2.3.3 AIR QUALITY

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.

In Germany the extraction of methane is supported by laws, contributing to minimize the risks of surface gas emissions and to reduce greenhouse gas emissions.

Finally, 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:

(a) If methane content in mined coal deposits was below 2.5 m^3 CH4/Mg DAF (Dry Ash Free):

• A hazard of dangerous CH_4 concentration on the surface implies no action to lower risks (no risk).

• A hazard of dangerous CO_2 concentration on the surface implies to forecast CH_4 and CO_2 migration together with potential zones of hazard. Guidelines for monitoring and prevention must be prepared. Risk after taking actions to lower it depends on the monitored concentration of gases: low ≤ 0.05 %; medium, between 0.05 % and 0.5 %; high, between 0.5 % and 2 %; and very high ≥ 2 %.

• A hazard of dangerous CO_2 concentration in buildings implies the monitoring of underground floors of the buildings. Risk after taking actions to lower it depends on the forecasted concentration of CH_4 and CO_2: low ≤ 0.02 %; medium, between 0.02 % and 0.2 %; high, between 0.2 % and 2 %; and very high ≥ 2 %.

(b) If methane content in mined coal deposits was above 2.5 m^3 CH_4/Mg DAF (Dry Ash Free):

- A hazard of dangerous CH_4 and CO_2 concentration on the surface implies to prepare forecasts of CH_4 and CO_2 migration from coal mine being closed together with potential zones of hazard and to prepare guidelines for monitoring and prevention. Risk after taking actions to lower it depends on the monitored concentration of gases: low ≤ 0.05 %; medium, between 0.05 % and 0.5%; high, between 0.5 % and 2 %; very high ≥ 2 %.
- A hazard of dangerous CH_4 and CO_2 concentration in buildings implies the monitoring of underground floors of the buildings. Risk after taking actions to lower it depends on the forecasted concentration of CH_4 and CO_2: low ≤ 0.02 %; medium, between 0.02 % and 0.2 %; high, between 0.2% and 2 %; and very high ≥ 2 %.

Poland also has criteria to be used during shaft closure, also according to the criterion of methane content in a coal deposit:

(a) If methane content in mined coal deposits was below 2.5 m^3 CH_4/Mg DAF (Dry Ash Free):

- A hazard of CH_4 explosion needs no actions to lower risk (no risk).
- A hazard of formation of atmosphere unsuitable for breathing needs no actions to lower risk (low risk).
- A hazard of asphyxiant CO_2 implies that monitoring CO_2 concentration in the air is needed. CO_2 concentration in the air should not exceed 0.5 % (medium risk).

(b) If methane content in mined coal deposits was above 2.5 m^3 CH_4/Mg DAF (Dry Ash Free):

- The hazard of a CH_4 explosion has a high risk, or a very high risk while closing two last shafts of the mine. In this cases, the actions to lower risk will be that the technology for closing the shaft should consider the type of backfill material (permeable, non-permeable) and the inflow of water into a shaft. It should be designed a simplified ventilation network: simulating calculations of ventilation parameters after excluding a mine working or mine workings from the model of a ventilation network. The ventilation must balance the methane to prevent exceeding 2 % CH_4 in the air. Also, monitoring CH_4 concentration in the air should be done and concentration should not exceed 2 %.
- The hazard of formation of atmosphere unsuitable for breathing has medium risk. The actions to lower risk will be the same as in the previous case.

- The hazard of asphyxiant CO_2 has a medium risk. The actions to lower risk should be to monitor CO_2 concentration in the air. CO_2 concentration in the air does not exceed 0.5 %.

The hazard of losing stability of work of the main fan after closure of a mine working or workings has a high risk, or a very high risk while closing two last shafts of the mine. The actions to lower the risk should be to use a technology for closing the shaft considering type of backfill material (permeable, non-permeable) and water inflow. To design a simplified ventilation network: simulation calculations of ventilation parameters after excluding a mine working or mine workings from the model of a ventilation network. And, finally, to change the fan performance characteristics undergoing calculations for maintaining a stables performance of a main ventilation fan.

3. The MERIDA Risk MANAGEMENT model

The main output of the MERIDA project is a risk assessment based planning tool that allows the design of a logical, step-wise approach to mine closure that can be progressively refined during the post-closure period to address all relevant environmental risks. This tool is based around three main components, modelling of the risks, risk assessment & evaluation and economic evaluation as shown in Figure 3.1.

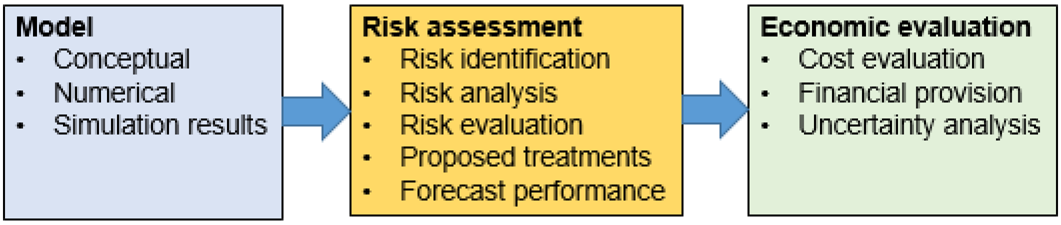


Figure 3.1: Components of the Risk Assessment Methodology

3.1 COMPONENTS OF THE RISK ASSESSMENT METHODOLOGY

3.1.1 MODELLING

The modelling of each of the environmental risks is a two-step process starting with the creation of a conceptual model. This is a representation of the particular hazard, its underlying concepts, pathways and receptors. This will define the questions to ask, the need to adapt the tools and techniques that will be employed in the prediction, the design of sampling programs and the assumptions and samples or data values to be used.

This is followed by numerical modelling which uses mathematical models to describe the physical conditions of geological scenarios using equations and collated data. Appropriate numerical simulation tools have to be selected according both to general underground coal mining expertise and to the track record of utilization and development within the company or by the experts that may cooperate with the work.

The first step in the numerical simulation should be the calibration of the models, with the objective of defining the most adequate strategy in order to achieve an acceptable degree of accuracy within the process with the smaller amount of information. For this purpose "case studies" from the same region or from similar environments should be used, in order to optimize the models in a way that they are able to reproduce the available measures. In this project case study sites were selected in Poland and Spain. The calibration process will also define all the data and relevant information that will be necessary to collect in order to feed the numerical simulation. Thus a sampling program must be developed before the numerical model is used to undergo the final simulation that will allow obtaining the estimated levels of risk.

As summary of the different methods utilized for both conceptual and numerical modelling is shown in Table (after Heikkinen et al, 2008).

Table 10: Types of Method used for Conceptual and Numerical Modelling

EMISSION ASSESSMENT	EXPOSURE ASSESSMENT
Measurement and Observation Methods	**Measurement Methods**
• Emission and load measurements • Measurements of properties affecting emissions (e.g. chemical stream pressure, solubility etc.) • Laboratory analysis	• Sampling through Personal measuring devices • Measuring devices for air, water, soil or sediment quality; • Remote sensing methods • Biological measurements (e.g. chemical residue, bioaccumulation, biodegradation, indicator specific etc.)
Simulation Tests	**Testing**
• Leaching tests • Simulation of hazardous situations • Simulations of accidents/impacts	• Laboratory testing • Field testing • Scale models
Statistical Methods	**Dosage Calculations**
• Sampling methods based on statistical distribution • Probability distributions, regression analysis	• Dosage calculation models taking into account exposure time, degradation time, accumulation etc
Modelling Methods	**Migration Models**
• Fault trees, event trees • Process models • Emission models • Moedls for assessing the functioning of protective structures • Failure analysis	• Models for transport and transformation of impurities in the air • Surface water models • Groundwater models • Multimedia models

Specific details on the modelling of the risks, outlining the conceptual models, the numerical models and the simulation results is given in Section 3.2.

3.1.2 RISK ASSESSMENT

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation. In the first stage, risk identification, all of the environmental risks affecting coal mine closure are identified. In many cases these major risks are known and include water management, air pollution issues, surface subsidence, residue deposits, soil pollution, abandoned facilities and, other cumulative environmental impacts. Cause-effect diagrams are used to determine the causes and consequences of each of these risks.

The second stage is risk analysis, the purpose of which is to determine the level of risk. The modelling, described earlier, simulates the outcomes of the risks, and these are compared with available risk criteria. The level of risk can then be determined by subjectively considering the likelihood and consequence dimensions using the integrated risk matrix shown in Figure 3.2.

1	INSIGNIFICANT: No impact; loss below 10,000 €
2	MINOR: Very low impact; loss between 10,000 € and 60,000 €
3	MODERATE: Significative impact; loss between 60,000 and 300,000 €
4	MAJOR: Significative impact; loss between 300,000 and 600,000 €
5	SEVERE: Serious impact event; loss between 600,000 and 2,000,000 €
6	CATASTROPHIC: Extremely serious impact event; loss above 2,000,000 €

A	RARE: Probably it will never happen
B	UNLIKELY: Not likely to occur in normal circumstances
C	POSSIBLE: May occur at some time
D	LIKELY: Expected to occur regularly under normal circumstances
E	ALMOST CERTAIN: Will occur or could occur within weeks or months

Likelihood rating	1	2	3	4	5	6
E	IV	III	II	I	I	I
D	IV	III	III	II	I	I
C	V	IV	III	II	II	I
B	V	IV	III	III	II	I
A	V	V	IV	III	II	II
	Consequence rating					

Figure 3.2: MERIDA Integrated Risk Matrix & Scales

Risk evaluation then involves comparing the results of the risk analysis with the established risk criteria to determine whether the level of risk, as it stands, is acceptable or if additional action is required. This decision making process is designed into the risk matrix whereby each combination of likelihood and consequence links to specific actions in the form of risk treatment as shown in Figure 3.3. The residual risk once these additional risk treatment options are identified can be determined using the same risk matrix.

I	VERY HIGH: Nothing can be left in this situation
II	HIGH: Strong investments will be necessary in order to control the risk. Measures should be adopted in a shorter period of time than with the medium risks
III	MEDIUM: Specific measures should be adopted and implemented in a short period of time
IV	LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.
V	IRRELEVANT: No specific action is required

Figure 3.3: Risk Action Table

The risk assessment process is detailed in Section 3.4.

3.1.3 ECONOMIC EVALUATION

Risk treatment alternatives and their associated monitoring programmes have to be selected under the base of a cost-benefit analysis undertaken through the use of common economic models in order to evaluate the costs and benefits of each specific measure. The economic evaluation of costs and benefits must consider those that might occur in the short run to those that might take place over a longer period of time, as in the case of the monitoring programmes.

The cost-benefit analysis is developed together with a sensitivity and uncertainty analysis on its variables. Sensitivity analysis is the study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input. It should be followed by an uncertainty analysis which focuses on quantifying uncertainty in model output. To undergo an uncertainty analysis on key variables a typical tool is the Monte Carlo simulation, a computerized mathematical technique that allows accounting for risk in quantitative analysis and decision making. Monte Carlo simulation furnishes the decision-makers with a range of possible outcomes and the probabilities they will occur for any choice of action.

This overall operational Risk Assessment methodology is shown in Figure 3.4. This methodology provides an organized information framework that can be used in future underground coal mine closures, independently of the main environmental problems they face. This methodology can also be applied to any alternative mine closure context such as open-pit mines, underground metal mines, etc. the difference being the specific environmental risk factors they face and the different numerical tools that may need to be applied.

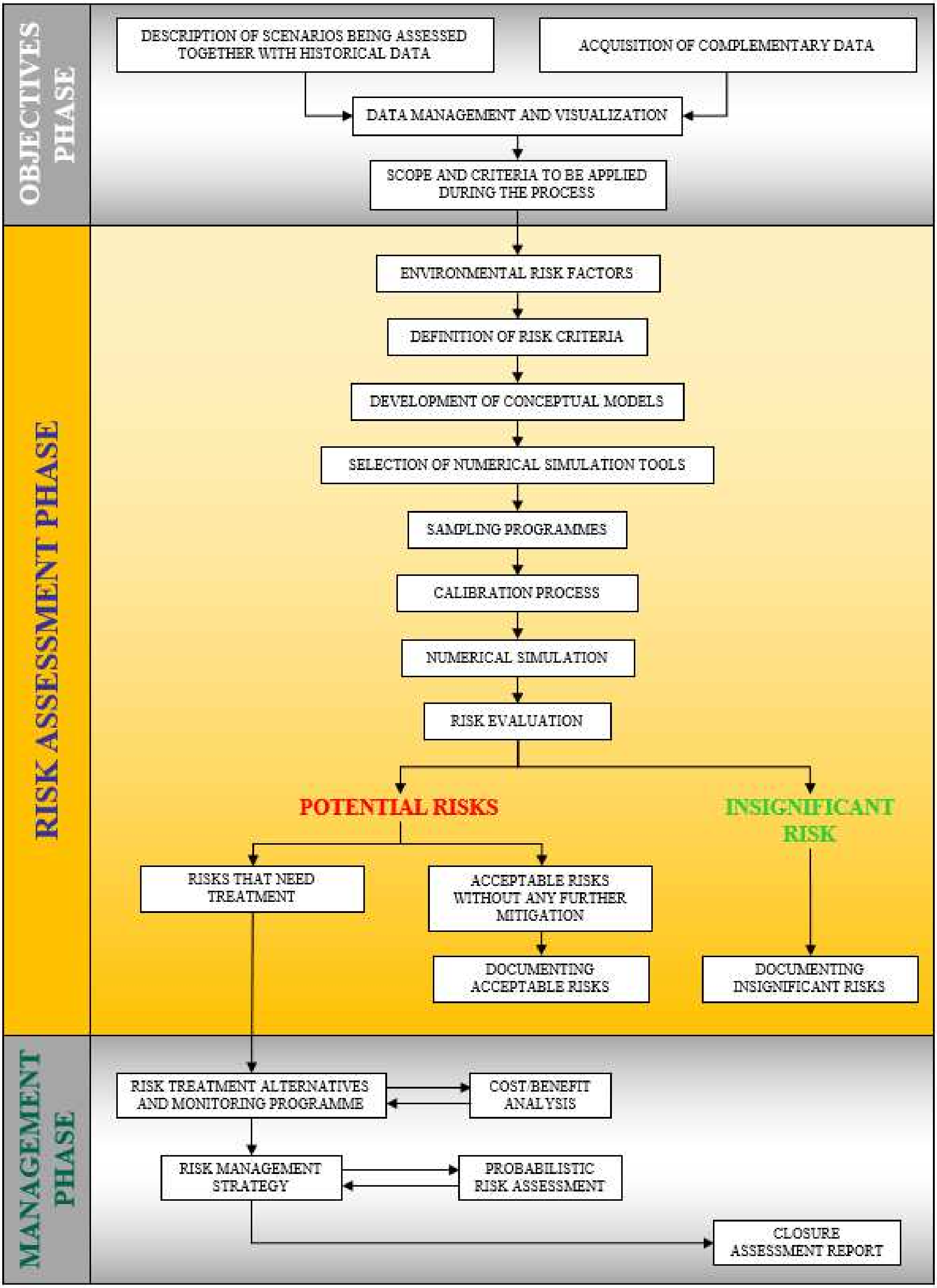


Figure 3.4: The MERIDA Risk Assessment Methodology

3.2 SUMMARY OF THE CASE STUDY SITES

The mine case studies that have been used in the project are the Rydultowy-Anna mining complex in Poland and the Mosquitera, Pumarable, San Antonio and Santiago mines in Spain.

3.2.1 POLAND

The Rydułtowy-Anna mining complex is in Southern Upper Silesia, in the south of Poland, near the Czech border. It sits in the Upper Silesian Coal Basin, which is the most important coal basin in Poland and one of the largest in Europe.

The complex is partially abandoned, with the rest undergoing closure. Prior to 2003 both the Rydułtowy and Anna mines were independent underground coal mines belonging to Rybnicka Spółka Węglowa (RSW).

In 2003 both mines were incorporated into the largest hard coal company in Europe, Kompania Węglowa (KW), and from 2003 until 2004 they were operated as a joint operation.

In 2016 Rydułtowy became part of the Polska Grupa Górnicza (PGG), the successor of KW, while Anna was transferred to Społka Restrukturyzacji Kopalń (SRK) which liquidates mines.

Figure shows the location of the Rydułtowy coal mine (pink) and the Anna coal mine (white) within Poland. In the bottom figure the shafts (small white circles) and proximity to major towns near these mines are shown (small and big pink circles).

Figure 3.5: Location of the Rydułtowy & Anna Mines

Rydułtowy Mine

The Rydułtowy mine is one of the oldest coal mines in Poland, with mining activity dating to 1792. In 2016 3,028 people were employed.

The mine is directly situated under the heavily urbanised areas of Rydułtowy, Rybnik and Radlin. The mining area is 45.19 km^2 with 6 shafts, 4 intake and 2 return. The average daily output ranges between 9000 and 9,500 tonnes per day.

Figure 3.6: The Rydułtowy Coal Mine

Anna Mine

The first mining activity at the Anna mine was in 1832. The mine has a mining area of 28.66 km^2. There are 5 shafts, however only two are still in use, and four mining levels; level 500 m (484 m), level 700 m (680 m), level 800 m (776 m) and level 1000 m (974 m). The closure process began in 2006 and the last longwall operation finished in 2015.

Figure 3.7: The Anna Coal Mine

3.2.2 SPAIN

The main Spanish mines in the project are Pumarabule and Mosquita, both owned by the national company, Hulleras del Norte SA (HUNOSA). The surface area of the mines in approximately 30 km^2 and they are at a depth of between 200 and 600 m. These are located in Asturias, in northern Spain as shown in Figure 3.8.

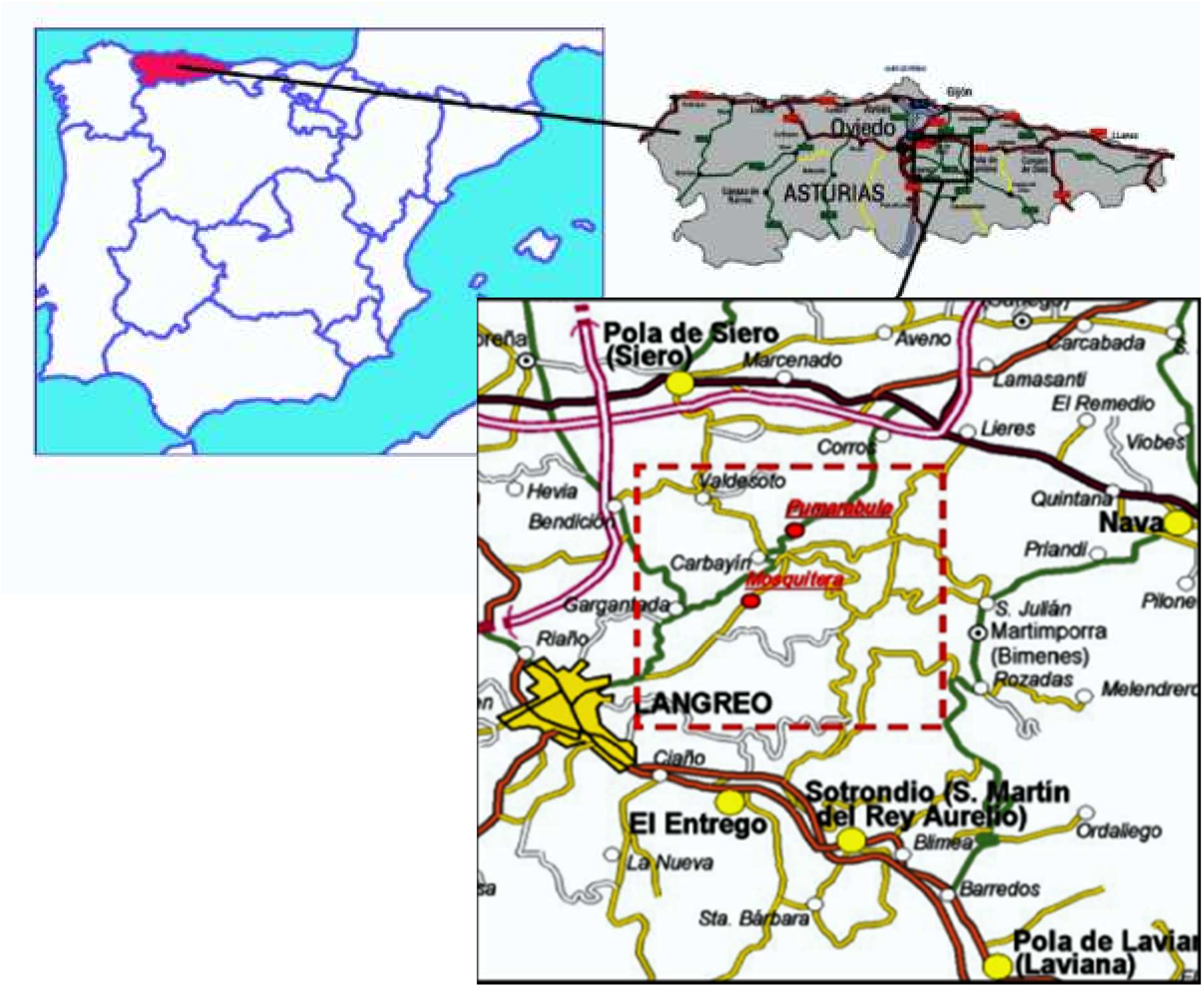


Figure 3.8: Location of Mosquitera and Pumarable Mines

Pumarabule

The two shafts of Pumarabule are located in the town of Carabyin Alto.

The Pumarabule shaft 1 was first excavated in 1916 and first operated in 1917. In 1957 a second shaft was sunk, Pumarabule in 1957 to 578 m. The shafts have 14 levels which range from 285.75 m a.s.l. (above mean sea level) to -292.74 m a.s.l.. In 1969 the Pumarabule mine was integrated with the HUMOSA Company. The mine closed in 2004 and pumping stopped in 2010. The flooding level should reach 235 m a.s.l.

Mosquitera

Mosquitera mine was first excavated in 1926, it has two main shafts, Mosquitera 1 and 2. Underground mining in Mosquitera 1 has a maximum depth of about 566 m, developed in 8 floors with 11 levels between 269.36 AMSL and -296.73 m a.s.l . Mosquitera 2 has 5 floors with a total of 7 levels and a maximum depth of 477.5 m (-204.50 m a.s.l).

On the 3rd of July, 2015, the water reached 229.14 m a.s.l. and the distance of the water level from the pit heads was 40.57 m. From the 9th of November, 2015, HUNOSA was authorized to increase the flooding level 5 meters, with a monthly increasing of 1 m. The flooding level should reach 235 m a.s.l.. Pumarabule mine 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.

Santiago – San Antonio Mines

This group of mines is also located in the Asturias to the south of Mosquitera. These additional mines were needed for the project to perform the ventilation study, which required a working mine connected to a closed mine.

Excavation at the Santiago mine began in 1951 and coal production ceased in 2018. The shaft goes from 281 m a.s.l. to -333 m a.s.l., with a deeper section to -400 m a.s.l., with 7 galleries. Although the coal is no longer being excavated there are still 250 workers.

The San Antonio mine began excavation at 1947 and coal production ended in 2003. The surface is at 302 m a.s.l. and the bottom of the shaft is -323 m a.s.l., giving the shaft a total length 625 m. There are 9 galleries and a direct link to the Santiago mine.

Canadín Mine

The Canadín mine is located close to the Mosquitera and Pumarabule mines and has a similar geological structure. This allowed the Canadín mine to be used for the subsidence modelling.

Excavation began at the Canadín mine in 1945 and coal production ended in 2012. The mine began to flood in 2014 and remains partially flooded. A pumping system was started in 2018. There are 4 shafts in the mine, the surface is 235 m above sea level and the bottom of the deepest shaft is -429 m.

3.3 MODELLING

In order to be able to assess the environmental risks being studied by the project (gas emissions, ground movement, groundwater and surface water) detailed numerical models had to be developed. These are summarised below and outlined in full in for each hazard later in this section.

<u>Gas Emissions</u>

Models were developed to predict gas emissions (CH4, CO2 and radon) from the case study sites (considering flooding and without considering flooding to the surface).

A model to estimate future emission rates was developed based on the methane-bearing capacity of the mined seams and the average methane emission throughout the life of the longwalls. Following this a second model was developed to identify methane flow paths and methane concentrations in individual areas using Ventgraph software. This software was also used to model radon effects. The results showed the places of possible gas outflow to the surface, as well as areas where risk of gas outflow possibly exists.

<u>Ground Movement</u>

Models were developed to analyse the behaviour of rock mass in a region of flooded coal mines in order to predict geomechanical and surface deformation,

The work consisted of selecting the suitable model describing the behaviour of rock mass fracture and then predicting the associated ground surface deformation. The Medium density change method was selected and a numerical model developed using Finite Element Method was developed. The results demonstrated the distribution of deformation indicators on the ground surface, such as displacements or stresses.

Ground Water

Models were developed to predict groundwater pollution impacts at the mine sites. The work included the building of the conceptual groundwater models, the implementation in the numerical software and the results and validation of numerical flow and transport models

For the Polish mines, a groundwater chemical flow model to estimate the environmental impact associated with water rebound was developed using FEFLOW. For the Spanish mines, a groundwater flow and solute transport model in flooded mines was developed with COMSOL Multiphysics. The results of the models showed water and pollution related variables of interest to assess the environmental risks associated with mine closure.

Surface Water

Finally models were developed to assess the surface water pollution impacts at the mine sites. 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 also modelled with the Windermere Humic Aqueous Model.

The results 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/ toxicity modelling gave the geochemical speciation results for the free metal ions.

A detailed description of each of these hazard models is given for each case study site is given in the Appendices. Each model has been broken down into its three component parts outlining detail of the conceptual model, the numerical model and the results of the simulations under the yellow tab in these sections

Models	→ **Conceptual** → **Numerical** → **Simulation Results**

3.4 RISK ASSESSMENT

Risk assessment is the second stage in the overall MERIDA risk management methodology (see Figure 3.4). The results of all the detailed risk assessments are given in the Appendices for the Polish and Spanish mines in the following order:

- Ground Movement;
- Ground Water
- Surface Water
- Gas emissions;

The risk assessment section of the examples is coloured orange and is separated into the components parts of the process. This order represents the risk assessment process which will then be described in detail in this Section.

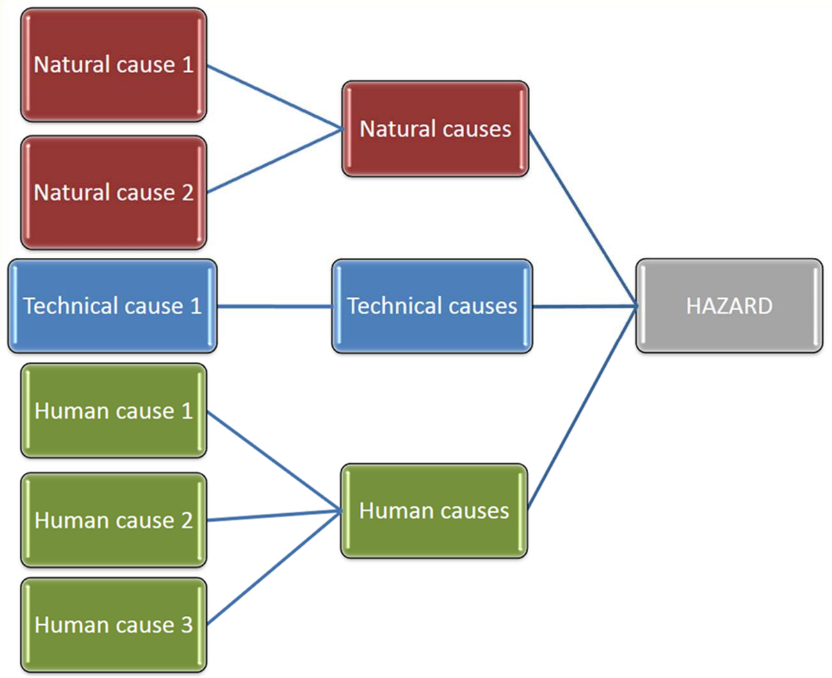
At the end of each assessment the economic evaluation is summarised in the pink tab.

Risk identification
Risk analysis
Risk evaluation
Proposed treatments
Forecasting performance
Economic Evaluation

At the stage of undertaking the risk assessment, the numerical modelling of the risk in question would have been carried out so that its potential consequences are known.

<table>
<tr><td>Risk identification</td><td>

Whilst the overall hazard in question is known, the objective of risk identification is to provide a detailed description of the hazard and any specific unwanted events that may arise from it. This is so that we can understand the hazard in question.
The results of the conceptual model would be useful for this as it would give more detail into the background, theory and sources of the hazard.
A cause-effect analysis (or tree diagram) is then created to provide a structured means of identifying and demonstrating what these causes are for the particular effect of the hazard. Each cause can be grouped as either natural, technical or human.



</td></tr>
<tr><td>Risk analysis</td><td>

The purpose of risk analysis is to develop an understanding of the risk arising from the hazard, in particular the liklihood of the unwanted event occuring and the consequence should it occur.
This should involve undertaking a descriptive analysis of the specific causes identified in tree diagrams previously.
Any factors that effect the consquences and liklihood should be identified.
The Numerical models that have been developed would be able to provide detail and quantify the consquences of these unwanted events. These can be compared with any relevent risk criteria that may exist for that hazard.

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isk evaluation

- ***The purpose of risk evaluation is to determine the significance and level of risk and to make a decision if the risk is acceptable or whether furthur risk treatment is necessary.***

- *This is done by subjectibly making a judgement on the level of conseqence and liklihood.*

- *The consequence is determined using the scale below. This should consider the **maximum reasonable** consequence of the hazard/impact.*

1	INSIGNIFICANT: No impact; loss below 10,000 €
2	MINOR: Very low impact; loss between 10,000 € and 60,000 €
3	MODERATE: Significative impact; loss between 60,000 and 300,000 €
4	MAJOR: Significative impact; loss between 300,000 and 600,000 €
5	SEVERE: Serious impact event; loss between 600,000 and 2,000,000 €
6	CATASTROPHIC: Extremely serious impact event; loss above 2,000,000 €

- *Subjectively determine the liklihood of the impact/hazard arising. This judgement should make reference to any **existing risk reducing measures** that may be in place as this effects the liklihood dimension of risk.*

A	RARE: Probably it will never happen
B	UNLIKELY: Not likely to occur in normal circumstances
C	POSSIBLE: May occur at some time
D	LIKELY: Expected to occur regularly under normal circumstances
E	ALMOST CERTAIN: Will occur or could occur within weeks or months

- *These values of consequence and liklihood are then combined on the following integated risk matrix below to produce a risk rating between (I)[Very high] and (V) [Very low or irrevelent].*

Likelihood rating	1	2	3	4	5	6
E	IV	III	II	I	I	I
D	IV	III	III	II	I	I
C	V	IV	III	II	II	I
B	V	IV	III	III	II	I
A	V	V	IV	III	II	II

Consequence rating

- *These ratings correspond to an recommended action level*

I	VERY HIGH: Nothing can be left in this situation
II	HIGH: Strong investments will be necessary in order to control the risk. Measures should be adopted in a shorter period of time than with the medium risks
III	MEDIUM: Specific measures should be adopted and implemented in a short period of time
IV	LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.
V	IRRELEVANT: No specific action is required

- *These actions determines the type, extent and time scale of the risk treatment that should be considered.*

Proposed treatments

- ***The objective is to determine proposed risk reducing treatment options that will reduce the residual risk to an acceptable level.***
- *Use the action level and the hierarchy of control to devise specific treatments to be undertaken to reduce risk for each impact.*
- *In determing the risk treatment options the following needs to be considered:*
  - *the severity and scope of the hazards concerned;*
  - *the state of knowledge reasonably available concerning that hazard or risk and any means of removing or mitigating that hazard or risk;*
  - *the availability and suitability of means to remove or mitigate that hazard or risk;*
  - *the costs and the benefits of removing or mitigating that hazard or risk.*

	• *The hierarchy of control should be used to determine what type of risk treatement options are necessary:*  o *Avoid – Design options to avoid impacts from the risks;* o *Minimise – put in place measures to prevent or minimise the impacts from the risks;* o *Mitigate – Put in place measures to mitigate the consequences of the risks.*
Forecasting performance	• ***The purpose is to consider the level of risk once the proposed risk treatment options have been put into place. The residual risk should be acceptable.*** • *Use the risk matrix again to determine the residual risk once the treatments proposed above are implemented.* • *Display this on the consequence/probability matrix and show the new risk rating.* • *Where possible a cost analysis of the risk treatement options can be undertaken. This involves detailing all the costs and investments necessary to determine Net Present Values in order to determine the financial provisions required for closure and post-closure stages. Then a sensitivity analysis and uncertainty analysis of the calculations can be conducted.*

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Appendix 1: Case Study (Poland)

Model: Conceptual model

During the implementation of the MERIDA project the analyses of the flooding of underground excavations have been performed using three new methods, which were:

- Pore pressure change method,
- Hydrostatic pressure change method,
- Mediums density change method.

Performing a number of analyses using above-mentioned methods, which confirmed the possibility of modelling the phenomenon of uplift of the ground surface because 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:

- the pores in the soil (rock) are completely filled with water, but the soil (rock) is above the groundwater table, in which case the volumetric weight is given by:

$$\gamma_{sr} = (1-n)\rho_s g + n\rho_w g \quad [kN/m^3]$$

where:

γ_{sr} is the volumetric weight of the soil (rock) above the water table;

n is the porosity of the soil (rock);

ρ_s is the specific density of the soil (rock);

ρ_w is the specific density of water.

- the soil (rock) is located below the groundwater table, in which case:

$$\gamma' = (1-n)(\rho_s - \rho_w)g \quad [kN/m^3]$$

where:

γ' is the volumetric weight of the soil (rock) above the water table.

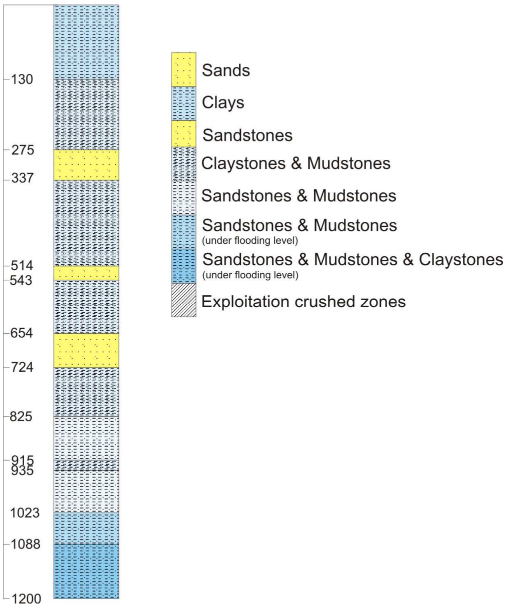
In this case, the pores are also filled with water, but according to Archimedes' principle, the weight of soil (rock) will be much smaller than the weight of soil (rock) located above the water table.

This results from the fact that water does not add weight to the granular soil structure, and additionally causes its buoyancy. This method offers simplicity of use and has a strong geomechanical basis.

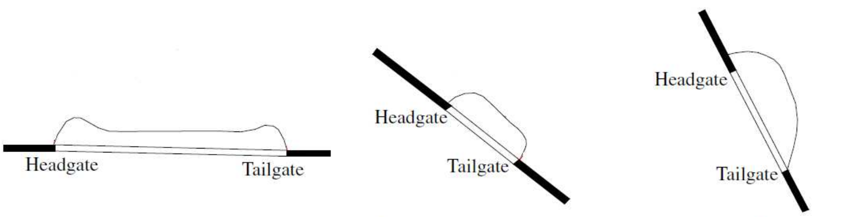
Model: Numerical model

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 idealized 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, the 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.



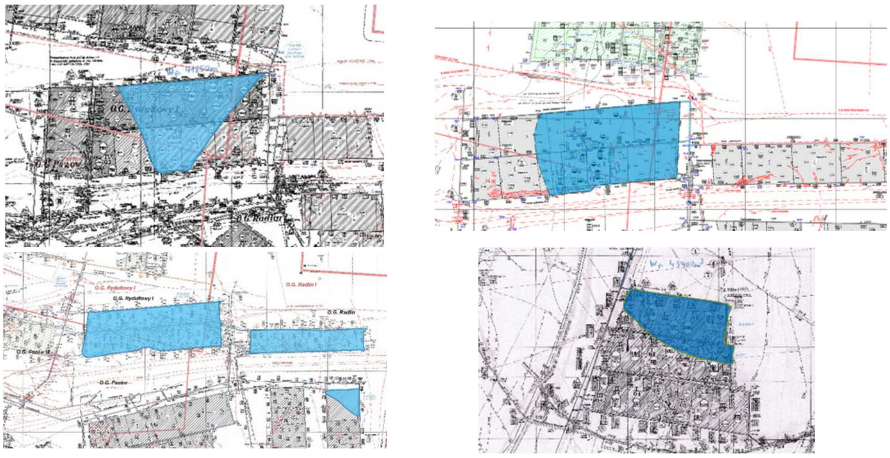
In addition to the physical-mechanical parameters of the rock mass, another important thing in numerical modelling of mining activity is the height of the cave-in zone. Depending on the region concerned, geology and rock mass parameters, it may range from 2-40 seam thickness. In addition to the height of the cave-in zone, it is important to choose the right shape of it. The shape of this zone varies depending on the inclination of the coal seam. Figure below presents schematically the possible shapes of a caved zone depending on the inclination of the extracted seam.



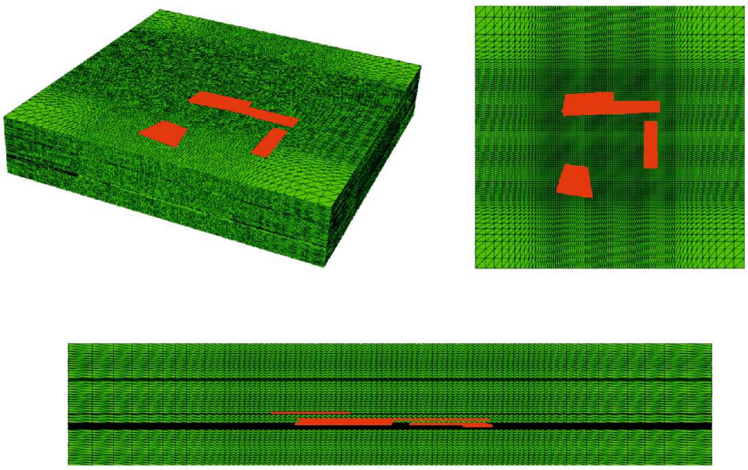
(a) Flat or slightly inclined seam (b) Inclined seam (c) Steeply inclined seam

In the case of the Anna mine, the example regarding flat and slightly inclined seams was analyzed. The shape of cave-in zone has been presented in the figure above (a).

For this reason, the shape of the cave-in zones for the Anna mine, corresponds to designated zones in the longwall panels, that will be flooded at the assumed level of the mine water table at a depth of -801 m.a.s.l. Figure bellow shows regions, which correspond to flooded zones.



Using prepared earlier information, the 3D numerical model using Finite Element Method, which represents analysed region of the mine, has been prepared. When building a numerical model, it must be consist of a sufficiently large number of elements. It will ensure high accuracy and quality of results from calculations. Generated model for Anna mine, with flooding zones marked in red, is shown below.



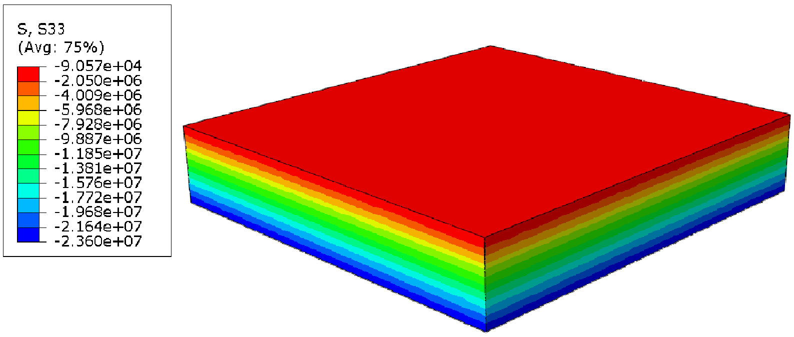
It is necessary to apply appropriate boundary conditions, i.e. displacement conditions of the model walls, gravity load, and application of pressure resulting from the initial state of stress and strain. Numerical calculations were performed for the constructed three-dimensional model in the following calculation steps:

1. Simulation of the initial state of stress and strain.
2. 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.
3. 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.

Model: Simulation results

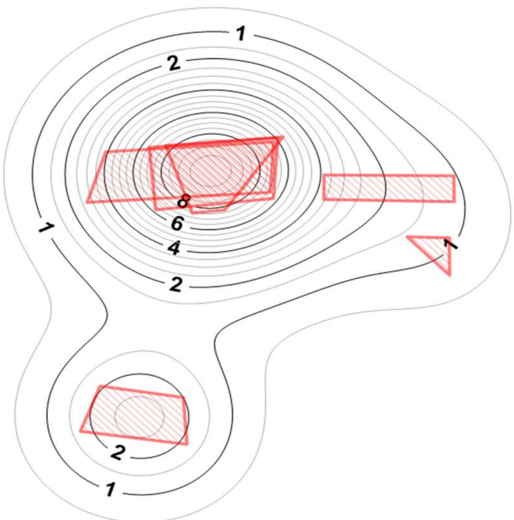
The results of the models allow to obtain the distribution of deformation indicators on the ground surface, such as displacements or stresses. In addition, distribution of these indicators in the rock mass can be achieved.

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

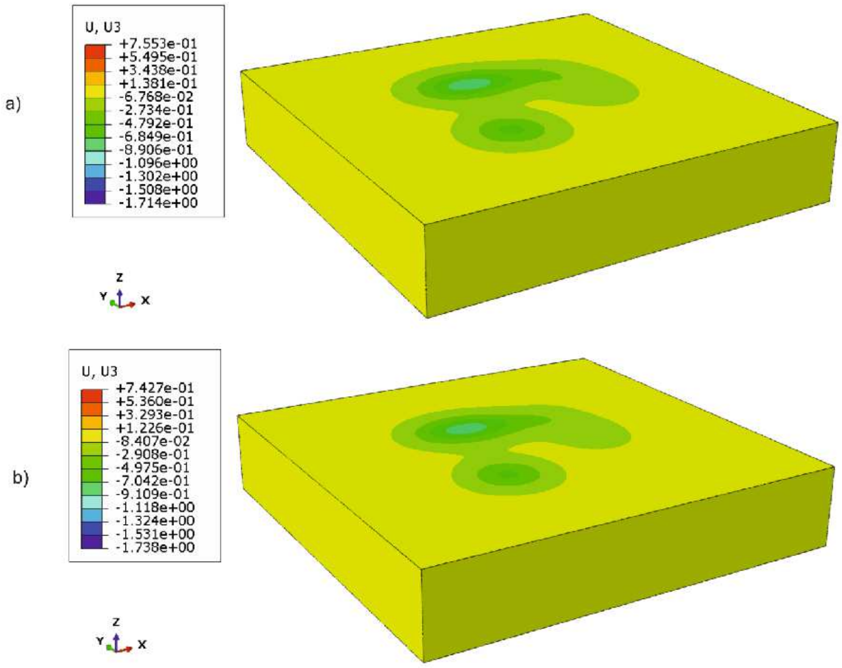


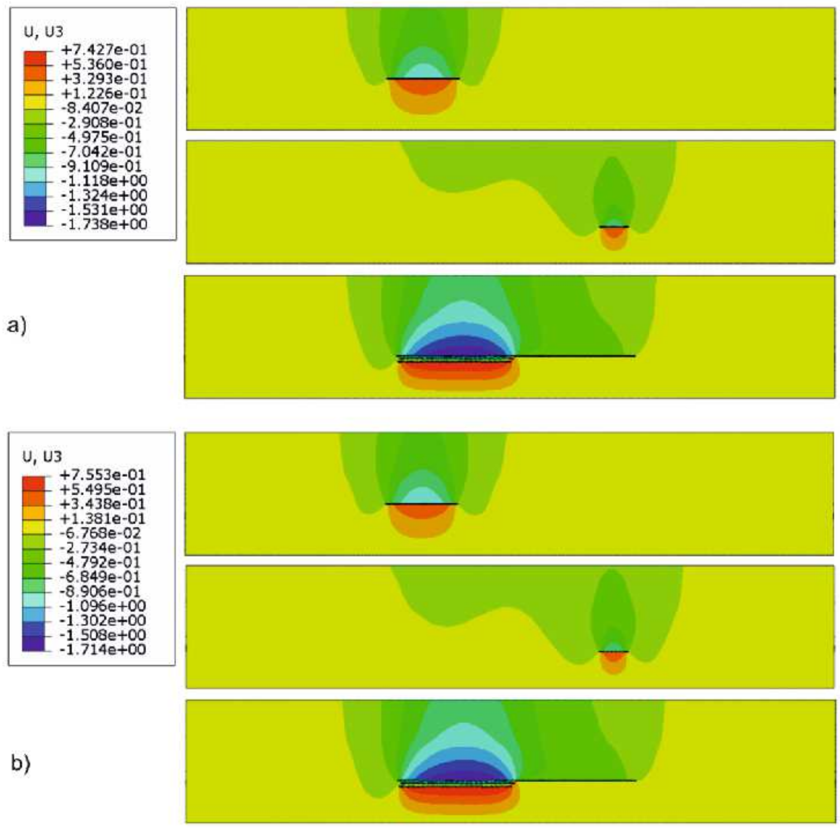
The second step of simulation was to perform simulation of mining activities. In case of Anna mine, the excavation with roof collapse has been performed. Simulation of seam exploitation has been modelled using equivalent elements with lowered physical-mechanical parameters applied into the cave-in zone. 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. 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.



Figures bellow shows respectively change in vertical displacements on the ground surface and in the rock mass for post-mining state **(a)** and after flooding of goafs **(b)**.





Risk assessment: Risk identification

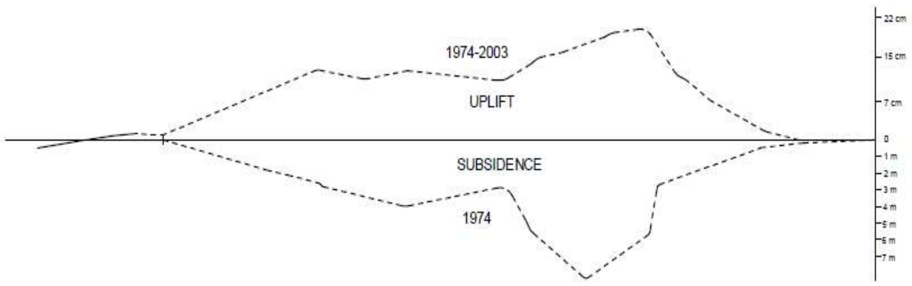
The liquidation of underground mines by flooding poses some geomechanical problems related to the changes in the properties of rock mass and the pressure inside it. These changes cause a disturbance of the initial state of stress and strain, which often results in the movements of the rock and soil strata.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

The diagram of the surface hazards related with mine flooding is presented below.

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 massiverock 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 centimeters) 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 define as small or very small in comparison to discontinuous deformation.Uplift and subsidence of the surface (Pöttgens, 1985):



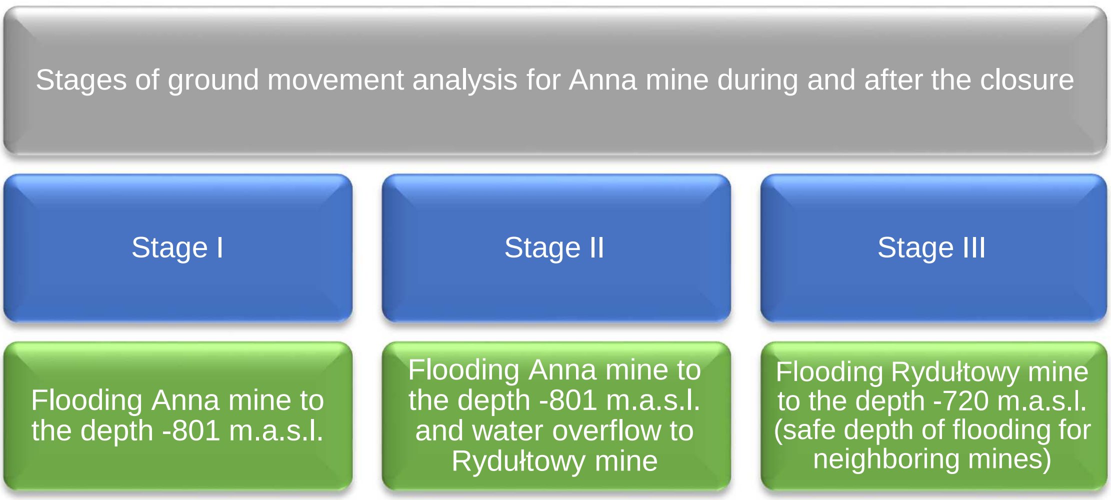
Discontinuous deformation

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, because of the displacement of the uplift and cracking in hard rock strata, it is possible to record dynamic phenomena in the form of tremors. 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 have been 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 neighborhood 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. The stages have been presented below.

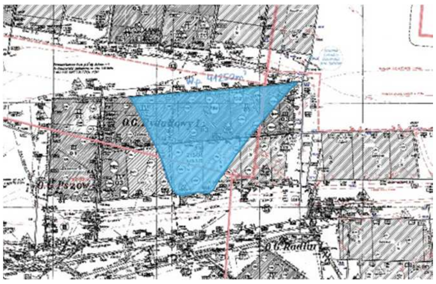


Due to the small difference in the depth of flooding and possible potential effects on the land surface in stages 2 and 3, they are analyzed together in further risk analysis. In the further part of the risk assessment associated with ground surface deformation for Anna mine is presented.

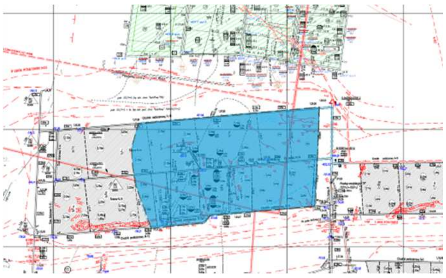
Risk assessment: Risk analysis (uplift)

Stage I: Flooding to depth of -801 m.a.s.l.

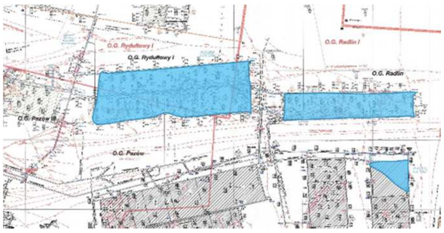
To assess the risk associated with ground surface continuous deformation, the deformation indicators have to be estimated, e.g. uplift (vertical deformation). The analysis consider flooding of the Anna mine to the depth -801 m.a.s.l. The flooding areas are presented on the figure below.



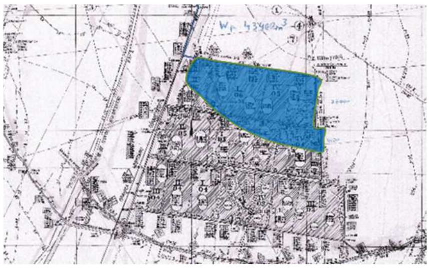
area in seam 703



area in seam 707

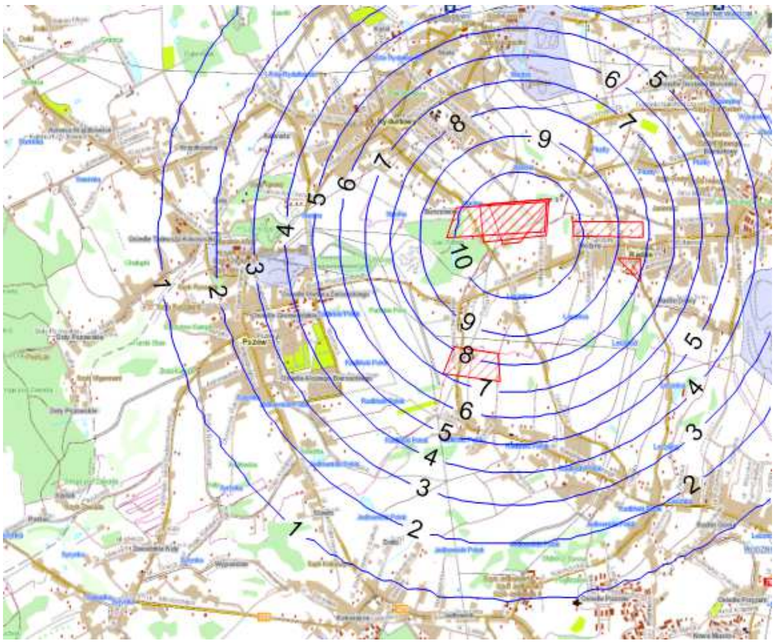


area in seam 713



area in seam718

Predicted uplift for Anna mine obtained using Sroka's method (area with uplift marked in blue and flooded regions marked in red).



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

Stage II: Flooding to depth -801 m.a.s.l. and water overflow to Rydułtowy mine

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 because of breaking the protections' tightness. The diagram below presents this situation. In these 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.

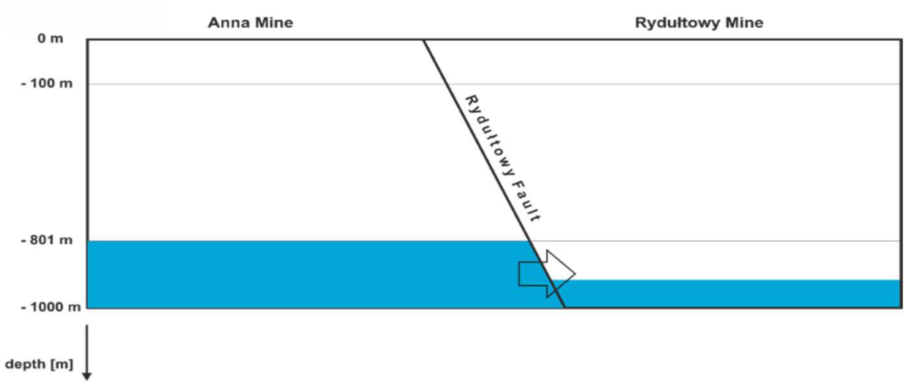
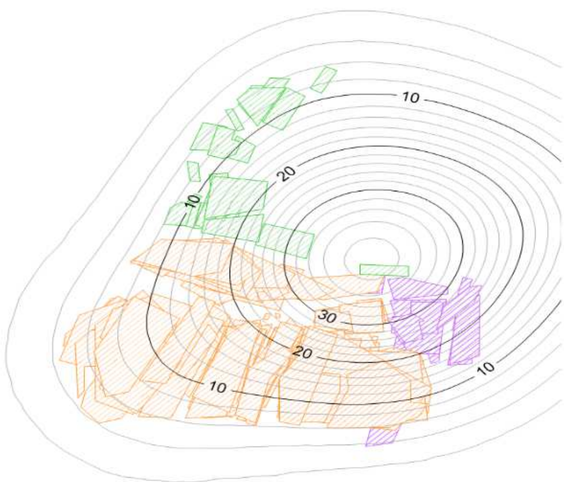


Figure below presents forecasted uplift, which is the result of flooding the workings located in all considered mines (Anna minefield - orange, Rydułtowy mine field - green, Marcel minefield - violet). The maximum uplift achieved from the forecasting calculations was approx. 40 mm. The results obtained in scenario 2 analysis due to the small difference in flooding depths between stage 2 and 3, were adopted in the further risk analysis for Stage III.



Risk assessment: Risk analysis (fractures, cracks)

Stages I, II and III

The probability of discontinuous linear type deformations occurrence on the land surface is an extremely difficult task to accomplish.

In addition, the influence range of this type of deformation is hard to predict due to insufficient data and information on the nature of the fault (e.g. fault permeability, fault filling and its physical parameters, fault roughness and others).

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.

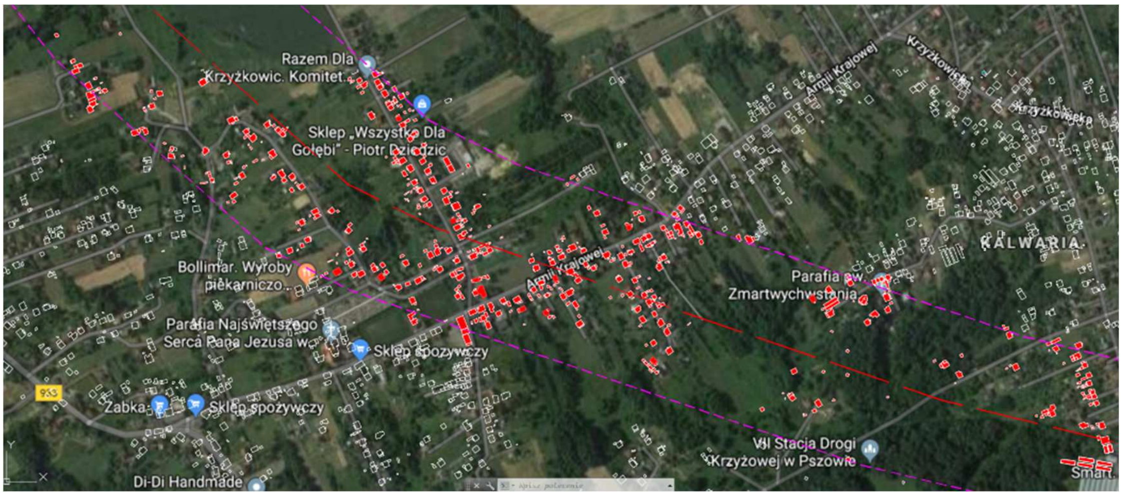
Authors experience and scientific literature, when dealing with the problem related to discontinuous surface deformations, indicate that flooding of the Anna mine to the depth approx. -801 m.a.s.l. will induct of sort incursion in fault region, which is the results of long-lasting multiseam mining operations in these area undergone some distortion (such as mine tremors, mine heading advancing pressure etc.).

Experience in the field of rock mass deformations, 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, the scale of consequences will be severe and cause serious damages to buildings located on the land surface.

The figure bellow illustrates a part of a region disturbed by geotechnical fault (Uskok Rydułtowski II - red dashed line).

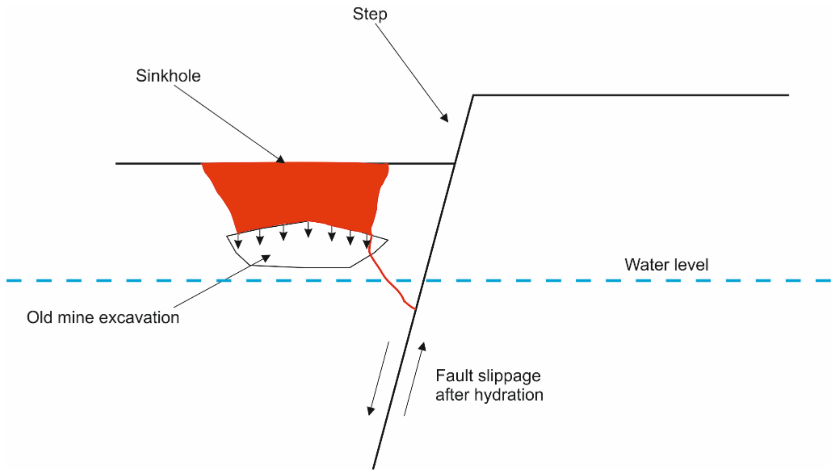
From the experience and research carried out by the authors, a zone of potential impact of the fault on objects located on the ground surface has been marked by dashed magenta line. The red color indicates building objects, which may be damaged if the fault will be reactivated.



Risk assessment: Risk analysis (sinkholes)

Stages I, II and III

The only situation when the sinkhole can appear during flooding operations is the one in which the slippage of the fault appears.



The formation of such deformation is favored by the existence of shallow old mining exploitation in a short distance from the fault. The Figure bellow 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 the fact that there is lack of important information (like predicted fault outcrop in quaternary).

Based on Stage I and II 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 it is possible in specific conditions).

Risk assessment: Risk evaluation (uplift)

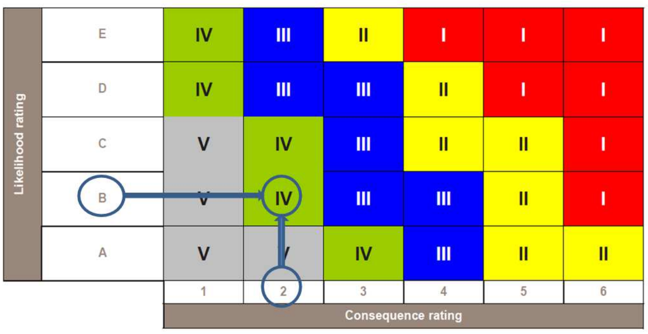
The first stage of hazard for Anna mine applies only to flooding the mine itself but in the second stage also applies to the Rydułtowy mine flooding by water overflowing from the Anna mine as a result of breaking the protections' tightness.

These 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, show 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 to 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 is need to be tell, that the risk of visible hazards and damages to structures on the ground surface is very low for Stage I and low for Stage II and III, when only continuous deformations are taken to consideration. The results obtained by applying the proposed methodology of risk assessment to Stage II and III are presented below.

Stages II and III



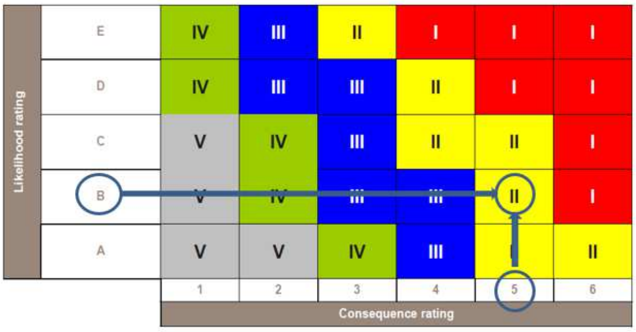
B UNLIKELY: Not likely to occur in normal circumstances

2 MINOR: Very low impact; loss between 10,000 € and 60,000 €

IV LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.

Risk assessment: Risk evaluation (fractures, cracks)

Stages I, II and III



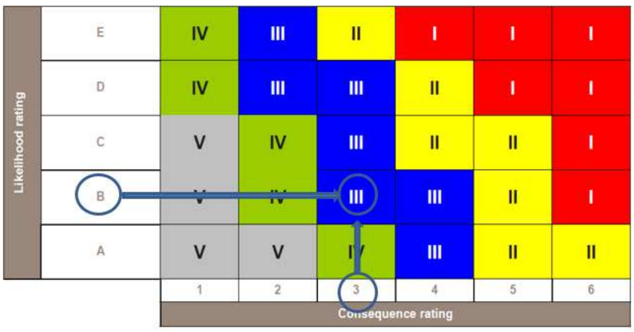
B UNLIKELY: Not likely to occur in normal circumstances

5 SEVERE: Serious impact event; loss between 600,000 and 2,000,000 €

II HIGH: Strong investments will be necessary in order to control the risk. Measures should be adopted in a shorter period of time than with the medium risks

Risk assessment: Risk evaluation (sinkholes)

Stages I, II and III



B UNLIKELY: Not likely to occur in normal circumstances

3 MODERATE: Significative impact; loss between 60,000 and 300,000 €

III MEDIUM: Specific measures should be adopted and implemented in a short period of time

Risk assessment: Proposed treatments (uplift)

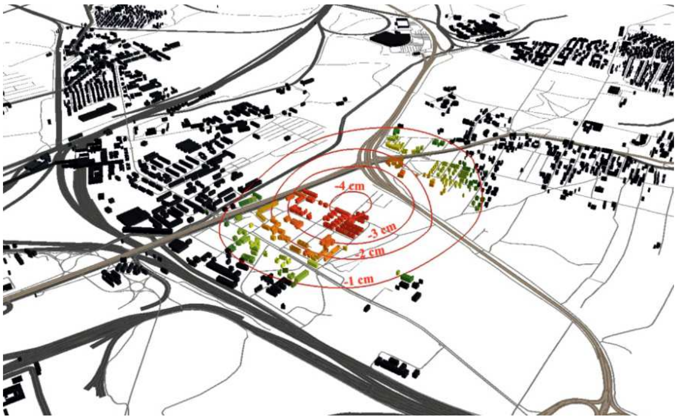
To minimise the existing risk, it is necessary to take steps to measure constantly deformation of the ground surface during the mine closure. In addition, in parallel with it, required is to monitor all the objects located on the surface, especially long structures, such as pipelines, warehouses, etc. Monitoring of the structures should be understood as:

- Measurement of object strains, displacements, tilt (especially long buildings),
- Regular objects inventory in search of damages (scratches, cracks).

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

Measurements of deformation of the land surface and objects can be carried out using traditional measurement methods, which are geodetic measurements. Levelers are used for this purpose. An example of digital leveler is shown below, a Leica LS10 (source: Leica).

To monitor surface deformation, advanced satellite technologies can be used to enable this task to be carried out effectively. DInSAR - Differenal Synthec Aperture Radar Interferometry is a modern technology of remote deformation measurement from a satellite level. Sample results are shown in the figure below (source: Sam Monitoring Satelitarny).



Risk assessment: Proposed treatments (fractures, cracks)

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.

The most important influence is the change of support conditions under some parts of foundations. It can be related with 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, 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 measurement of object strains, displacements and 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.

Risk assessment: Proposed treatments (sinkholes)

As was mentioned in fracture and cracks analysis, 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.

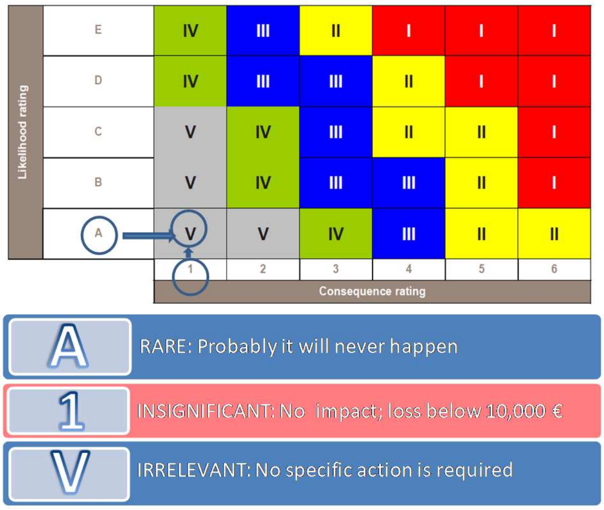
Taking the above facts into account, to minimize the existing risk for buildings currently in the zone of potential impact of linear discontinuous deformation, in the area of the flooded Anna mine, it is necessary to take steps to detailed inventory of old shallow excavation and then to backfill them 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.

In addition, if instabilities in the soil base are revealed in the endangered areas, reinforcing and sealing injections may be used. 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.

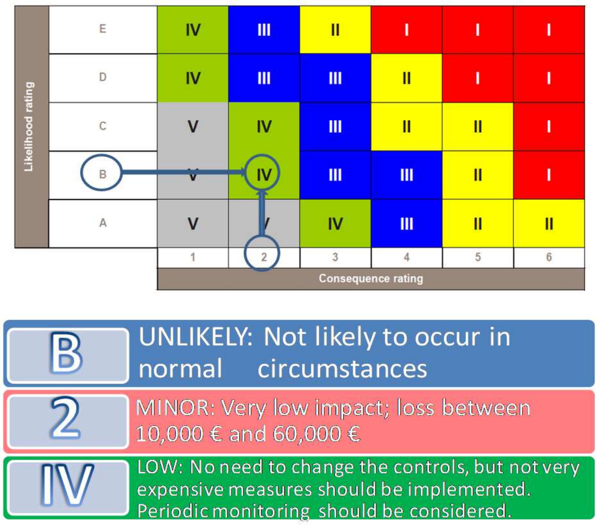
Risk assessment: Performance forecast (uplift)

The proposed measurement methods will reduce the likelihood of damage to ground and underground infrastructure because of uplift of the rock mass. It is impossible to relocate the whole infrastructure located in the uplift influence area. On the other hand, the implementation of appropriate monitoring methods will lead to a reduction in the effects of liquidation process carried out in the mine and a quick response to the appearing rock mass deformations. The result will be a reduction in mining damages. The implemented solutions aimed at minimizing the risk will reduce the likelihood of mining damage, but this will not change the level of risk for stage I, II and III.

Stage I



Stages II and III

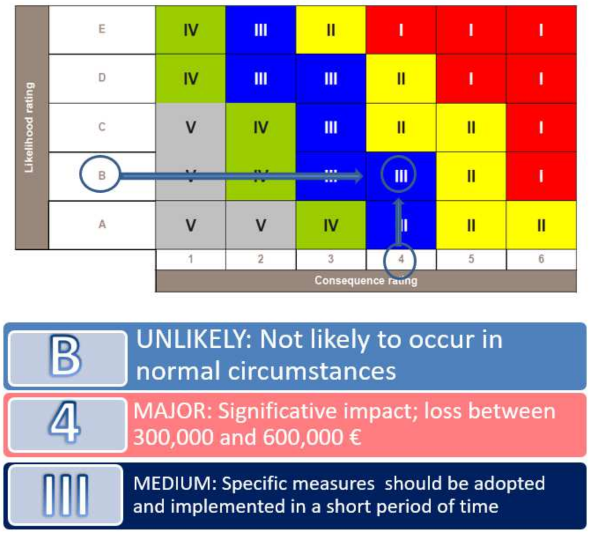


Risk assessment: Performance forecast (fractures, cracks)

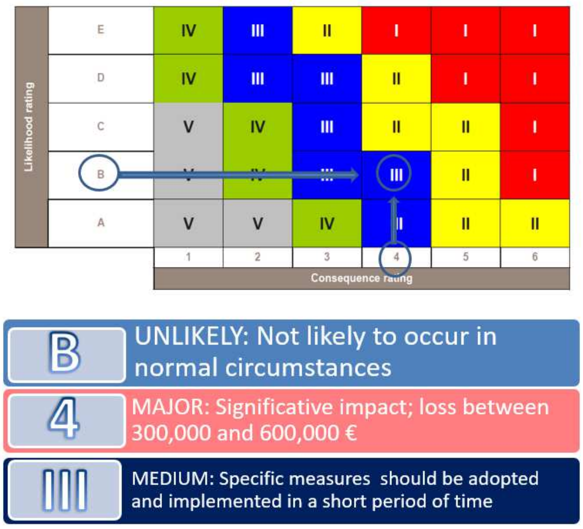
The proposed treatments will reduce the likelihood of damage to ground and underground infrastructure. However, as was mentioned earlier, buildings and other unprotected structures cannot resist efficiently influences of discontinuous deformation without significant damages, including full destruction of a structure.

Implementation of appropriate monitoring and proposed protection methods will lead to a reduction in the effects of liquidation process carried out in the mine and a quick response to the appearing rock mass deformations and will change the level of risk for Stage I, II and III. The results obtained by applying the proposed methodology of risk assessment are presented below.

Stage I



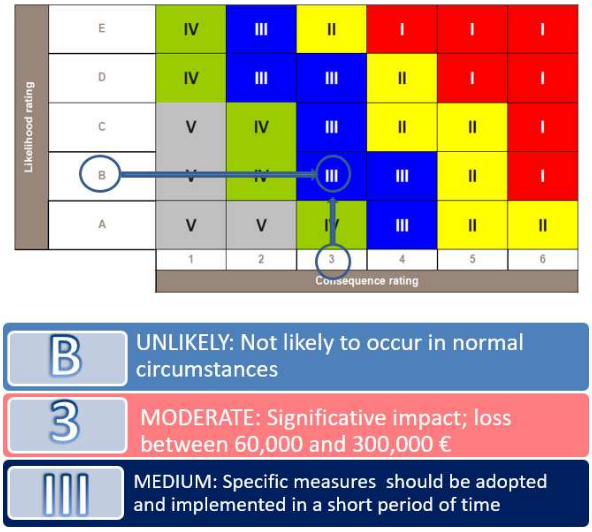
Stages II and III



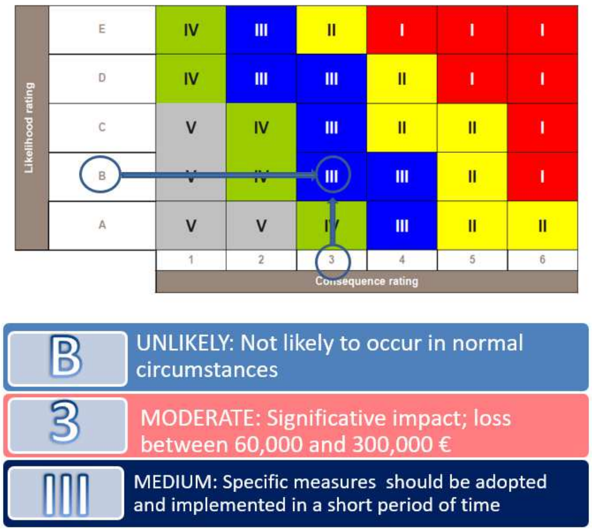
Risk assessment: Performance forecast (sinkholes)

The proposed treatments will not reduce the likelihood of damage to infrastructures. Buildings and other unprotected structures cannot resist efficiently influences of discontinuous deformation (especially surface type) without significant damages, including full destruction of a structure. Implementation of appropriate monitoring and proposed protection methods will not lead to a reduction in the effects of liquidation process carried out in the mine and will not change the level of risk but will enable quick response to the appearing rock mass deformations. In the case of the flooding of the mine to the near surface level (up to the level of the subsurface layers), it is necessary to take into account the possible activation of faults in the area mining activity, which can have a significant impact on changing the level of risk associated with surface deformation.

Stage I



Stages II and III



Economic evaluation: Cost evaluation

According to the previous information, in the case of uplifts, annual campaigns should be developed during the flooding and during the following seven years, as it is two years more than the maximum period of subsidence, being a good safety margin until the end of the uplift.

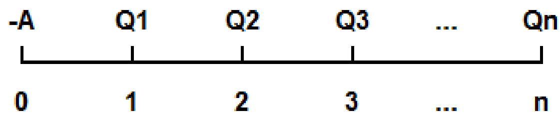
The cost of an annual geodetic campaign covering the area of influence can be estimated in:

Yearly geodetic campaign = 60,000 €

The implementation of appropriate monitoring methods will lead to a reduction in the effects of liquidation process carried out in the mine and a quick response to the appearing rock mass deformations. The result will be a reduction in mining damages.

On the other hand, the only possible action for both fractures and cracks, and sinkholes, is to monitor the affected area, something that can be considered as included within the annual geodetic campaign for uplifts.

Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 0 €

Q1, Q2, Q3, Q4, Q5, Q6 and Q7 = - 60,000 €

k = 5% ; n = 7

Calculating the Net Present Value in order to determine the financial provisions required for closure and post-closure regarding groundwater risks will be:

NPV = - 347.182 €

Economic evaluation: Uncertainty analysis

In order to establish which distribution function will be selected for the global NPV estimation, a bounded Johnson distribution for the yearly geodetic campaign cost will perfectly fit as it is used for modelling expert opinions, project management and cost analysis. It is used commonly for the modeling of expert opinion, project management and cost analysis.

It will have the following parameters: α1=2, α2=2, a=54,000 and b=66,000, with static value 60,000. With this distribution function the NPV will be -331,868, €, with a maximum of –317,480 €, a minimum of -359,141 € and a standard deviation of 6,740 €.

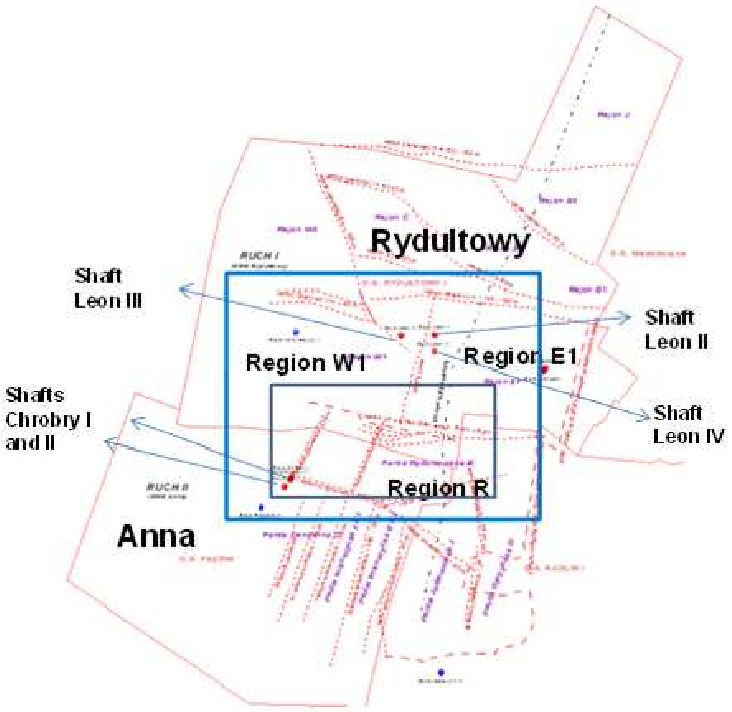
Model: Conceptual model

A conceptual model aimed at describing the natural inflows at the two mines, Anna and Rydułtowy 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 Rydułtowy mine, the conceptual groundwater flow model for the mine area of interest covers both Anna (Region R) and Rydułtowy mines.

In this region, a number of faults and a fault zone are the natural borders that divide the mining area into smaller panels. The Rydułtowy 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.

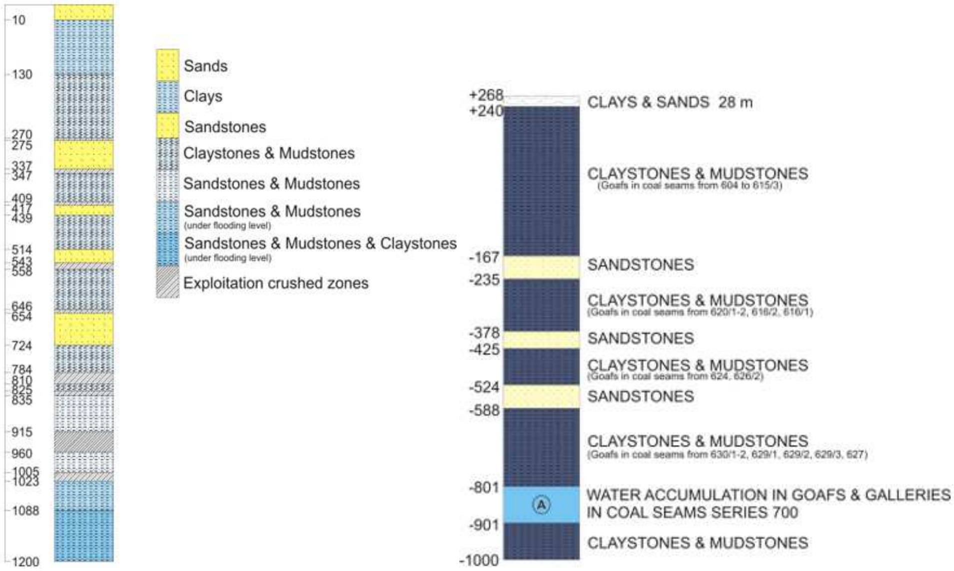
In Anna mine, mining operations were conducted in region R until recently (2015). In order to represent the groundwater system effectively, the initial model domain was later extended to include the southern part of Rydułtowy mine, in addition to the region R of Anna mine.



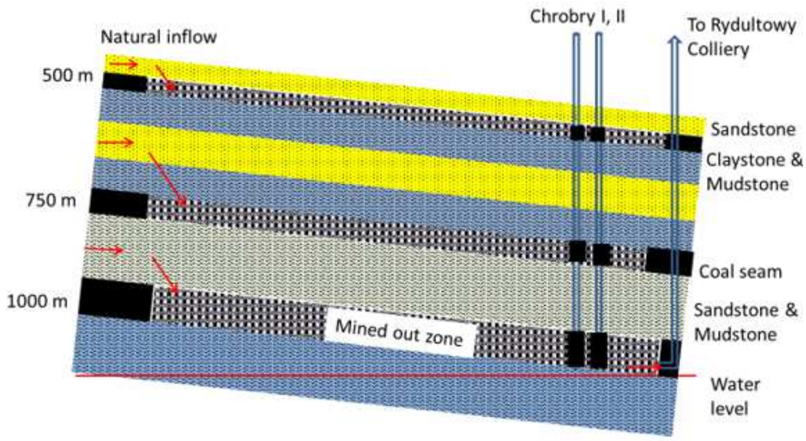
Flow rates, for both mines, are used to develop the conceptual model and validate the numerical model. The inflow rate for Anna mine is found to remain largely constant at about 1.3 m^3/min up to 2010, and then it declined gradually to ~ 0.8 m^3/min by 2016. The level at 500 m has the lowest inflow rate, whereas level 700 m has the highest. The Rydułtowy flow rate is much higher at ~ 2.2 m^3/min, reflecting the fact that the 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 a 10-layer simplified stratigraphy for both Anna and Rydułtowy 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 on the above simplified stratigraphy, a 9-layer conceptual model is developed, including three mine levels at 500 m, 750 m (combining the two at levels 700 m and 800 m respectively) and 1,000 m. The overlying sandstone formations provide the sources for natural inflow into mine level 500 m and 750 m, while the sandstone and mudstone formation for the mine level 1,000 m.



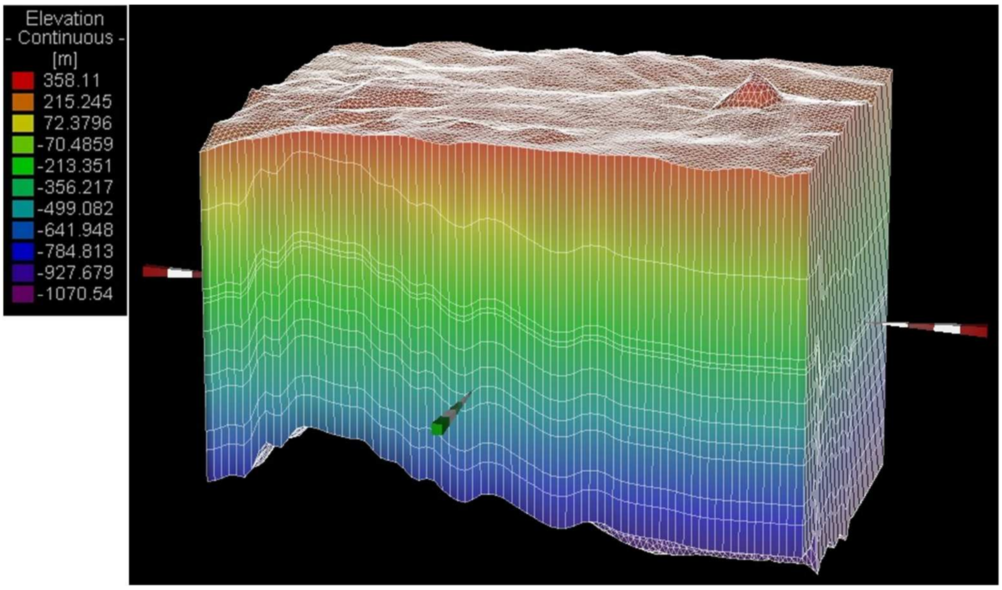
Standard (saturated) groundwater flow equation is selected, applying Darcy's equation. Though this option is selected, the model is able to account for phreatic conditions.

Boundary conditions: calculate the hydraulic head distribution between the upstream and downstream boundary, two wells, with a pumping rate of 900 m³/d and 1,000 m³/d, respectively located in the southern part of the model. These are used to represent a number of large well fields that exist in the region.

Model: Numerical model

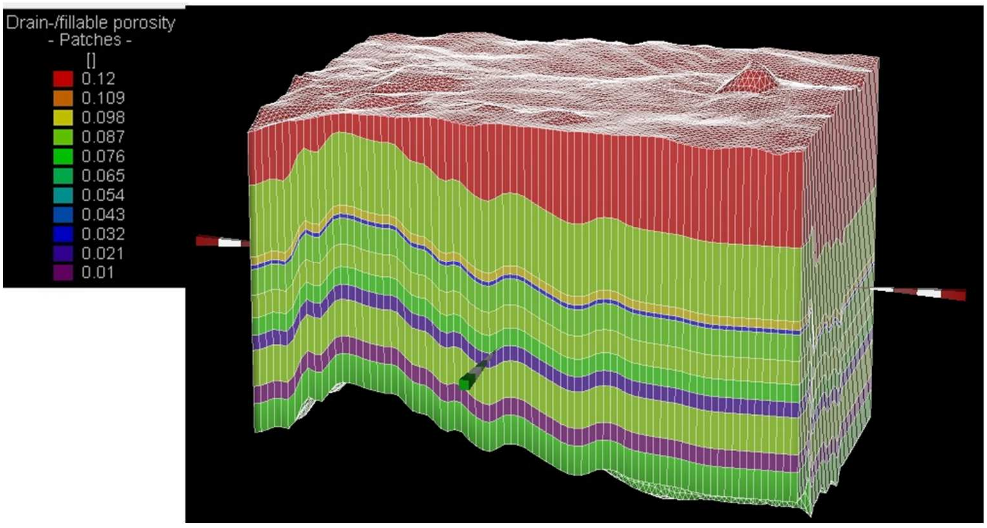
FEFLOW, a Finite Element subsurface FLOW and transport model is used for the development of the numerical model. The elevation data for each of the layers were extracted from the Digital Elevation Model for the deeper horizon and the remaining stratigraphy in the model region was calculated based on the thickness and depth of each top layer. These were used as the basis for the regionalization 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 ground water model are formed by combining the top 10 layers in the 25-layer stratigraphy. The three layers representing the aggregate coal seams are layers 4, 8 and 10. Specifically, layer 4 represents coal seam 623 and 624, overlain by a sandstone layer; layer 8 represents coal seams 626/2, 629/1, 629/2-3 and 630/2, overlain by a layer consisting Carboniferous claystones and mudstones, which in turn is overlain by a sandstone layer; layer 10 represents coal seams 703/1-2, 7-5/2-3, 707/1-2, 708, 712/1-2, and 713/1-2, overlain by a layer made up of Carboniferous sandstones and mudstones.

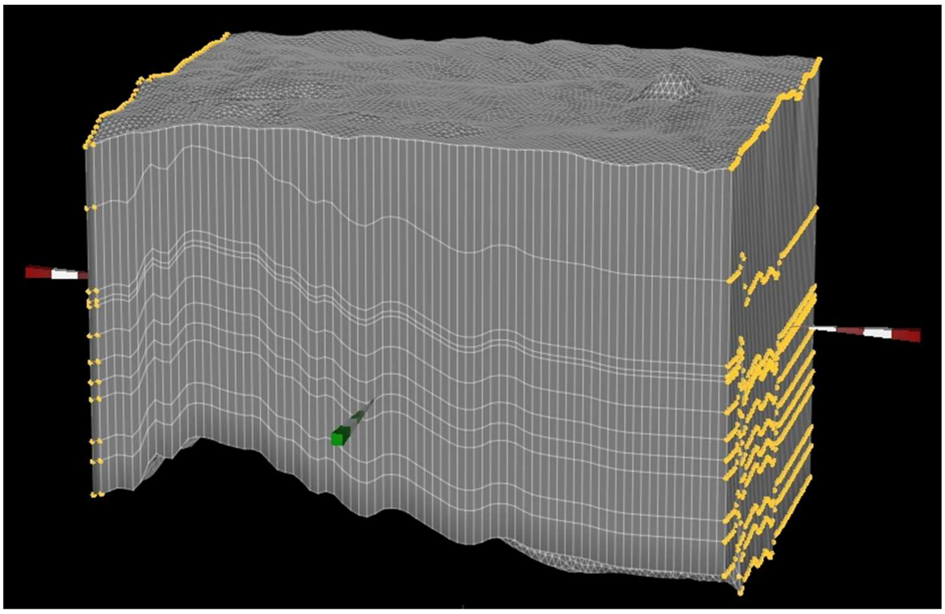


Next, material properties, such as hydraulic properties of water-bearing sandstones and mudstones at different depths (open porosity, specific yield and permeability) were assigned. These are considered to show a marked downward trend with depth. The results of laboratory and field investigations indicate that Carboniferous sandstones and mudstones below the depth of 700 – 800m are practically impermeable. However, in the areas of mining, where slides, cracks and distressing of rocks, accompanying mining excavation, 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 the different layers, taking into account the impact of coal extraction and caving on the overlying strata. 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.



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. Precipitation at the surface could be applied, but it is not considered to be a direct source for recharge at depth and its influence to the mine inflow is considered to be a minimum.

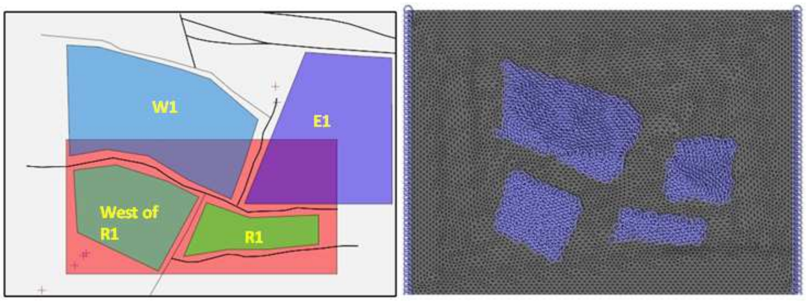


Shafts are introduced to the model as multilayer wells for simplification. Features such as the pumping rate, the radius of the well and the elevation of the top and bottom end were assigned. These values were assigned based on the extracted elevation model, field measurements and literature review.

	TOP	BOTTOM	RATE	RADIUS
Chrobry I	268.78	-804.22	2,000	2.1
Chrobry II	268.78	-739.72	0	2.1
Jan	279.22	-426.78	0	2.1
Leon IV	175.26	-900	2,000	2.1

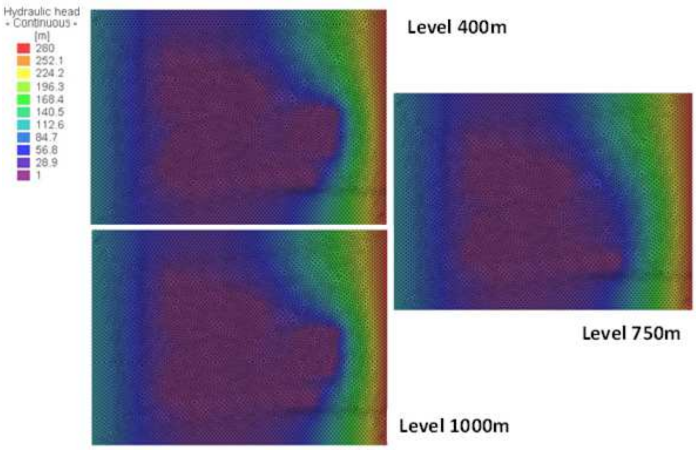
Model: Simulation results

The four mining regions, which are considered to simulate mine inflows, are the W1 and E1 regions in Rydułtowy mine, and the R1 and the west region in Anna mine. Sinks are created in the three coal seams in the model, to which reduced hydraulic head (~1m) are assigned.



The model 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.

Considering that there are other active mining regions, in addition to W1 and E1, in Rydułtowy mine, the simulated flow rates are somewhat 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 are simulated.



Dewatering of closed mines is expected to continue, as many of the USCB 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 below ground region will be flooded by rising ground water. It may occur in areas where shallow water-bearing layers are not isolated from the carboniferous rock mass.

A groundwater flow and contaminant transport model through a reactive multispecies coupling is set up to evaluate the overall threat to groundwater quality, and to quantify the potential pollution at the shaft, discussed in the risk assessment.

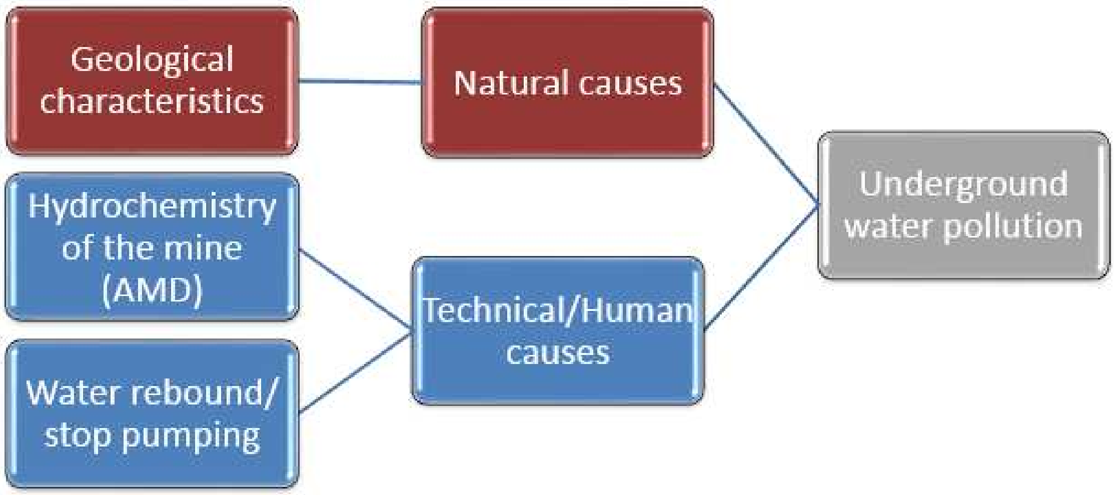
Risk assessment: Risk identification

For the case of Anna-Rydułtowy 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. This is important as the mines are connected and pumping at Anna mine is continuing to protect the currently active Rydułtowy mine.

The hazards and sources of harm were identified.

As the mine hydrochemistry has shown heavy metal concentrations below 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.

In a simplified "cause-and-effect" diagram, we show the identified causal factors (on the "left hand side") influencing the level of risk associated with the groundwater quality. The contributory factors were grouped into two main categories, consistent with the other risk assessment components.



Besides the above factors, any interaction/communication with other mines, such as Anna with Rydułtowy 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.

The "source-pathway-receptor" concept for the groundwater chemistry risk evaluation will be used. Under the SPR model, groundwater itself can be seen as the pathway element, allowing transport of contaminants from the source to the target.

Targets could include drinking water supplies either in the vicinity of the input or a receptor some distance down-gradient of the input such as agricultural and industrial abstractions and surface water aquatic ecosystem.

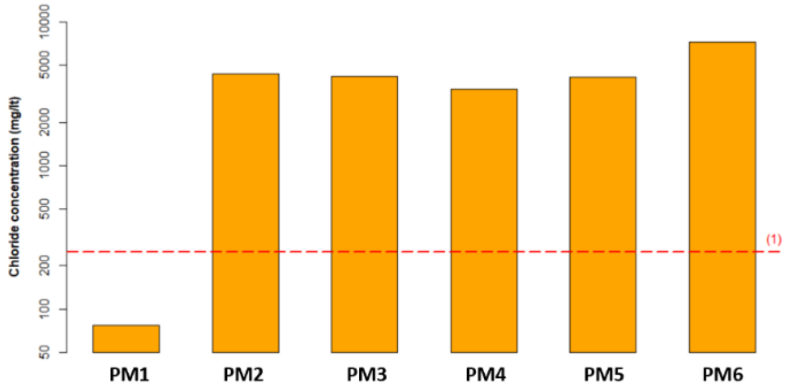
Risk assessment: Risk analysis

Comparison with risk criteria

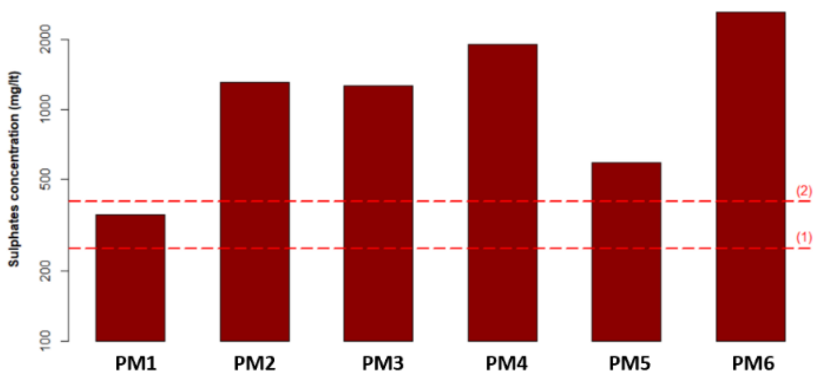
Groundwater sampling from Chrobry I shaft at different depths (PM1-shaft bottom at 500m, PM2-shaft bottom at 700m, PM3-drainage road at 800m, PM4-main draft at 1,000m, PM5-capacity gallery at 1,000m and PM6-drift at 1,000m) were carried out, focusing on those cations and anions with high concentrations. In order to determine the groundwater quality and the extent of any potential groundwater pollution around the mine, the level of each substance was first compared to the current defined risk criteria and international guidelines for drinking, irrigation and other water uses.

One of the main problems connected with the hard coal mining is the utilization of mine waters related to salinity (EC, sulphates and chlorides), as these are the parameters of concern that are typically regulated by the environmental authorities.

The sulphates, 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. These values also exceeded the guidelines for drinking water quality, prescribed by the World Health Organization, 250 mg/l and 1,000 µS/cm for sulphates and EC respectively.



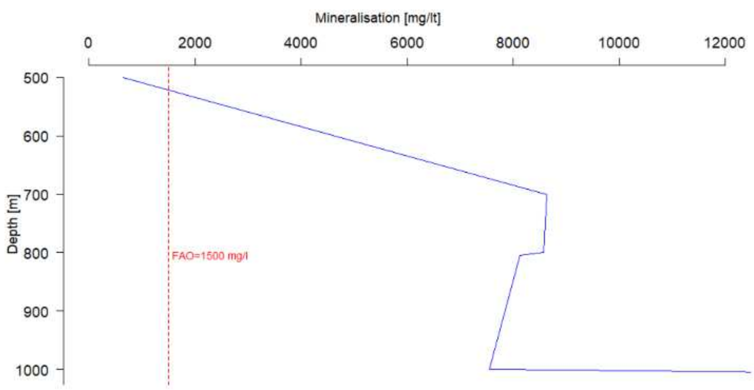
(1) Drinking standard: 250µg/lt (WHO and US.EPA Ambient Quality Criteria)



(1) Drinking standard: 250µg/lt (WHO and US.EPA Ambient Quality Criteria)
(2) Drinking standard: 400µg/lt (WHO Criteria for gastrointestinal effects)

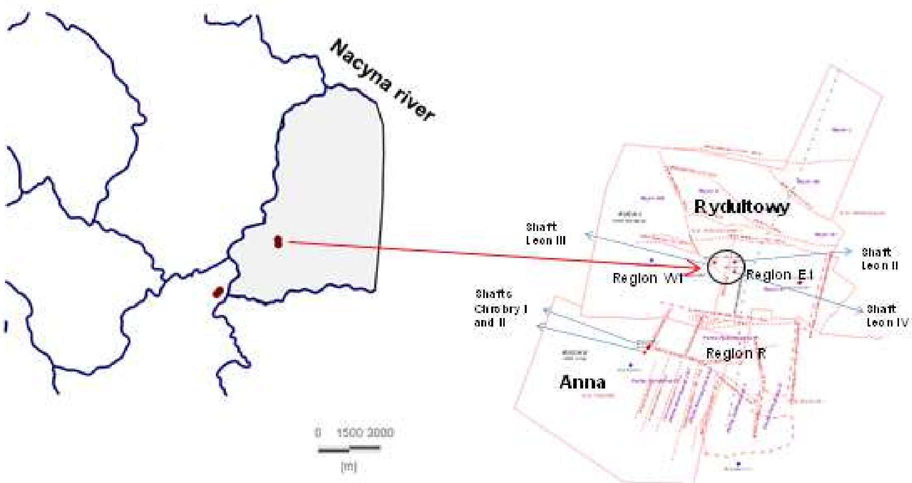
Iron and manganese levels ranged between 5.1 to 42µg/l and 2.2 to 250µg/l, respectively. An aesthetic limit at 300µg/l and 100 µg/l for iron and manganese, respectively has been set up. Iron levels were far below this level, without any adverse effect. Manganese levels were exceeding this level at two occasions, at PM1 and PM3.

Anna mine, based on the TDS levels (from 646 to 13,650 mg l^{-1}, with avg. 8,087 mg/l), exhibited a high mineralization, with medium to strongly mineralized waters – generally described as *saline waters*, due to high Na and Cl levels.



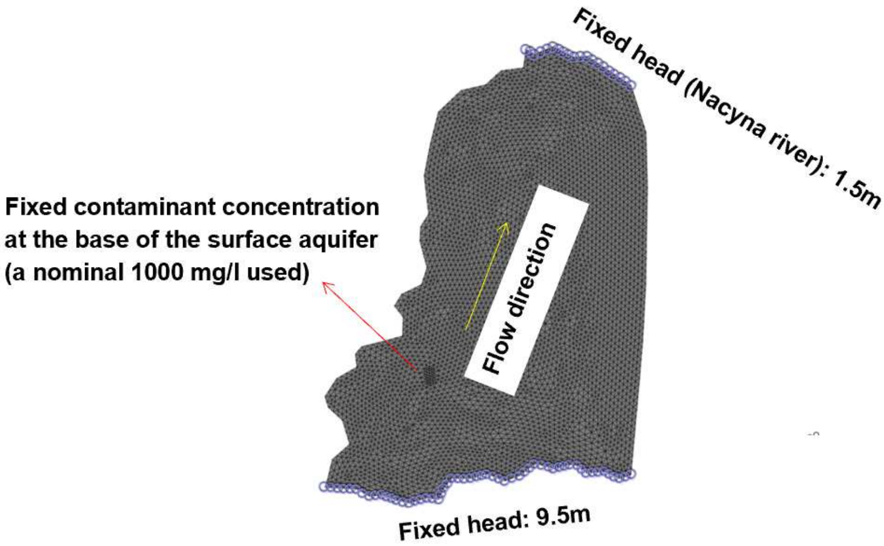
Development of a surface aquifer model for contaminant transport

Considering that risk for groundwater pollution around a deep mine would only be the case when the Rydułtowy mine also closes down, and the water table rebounds as the pumping is terminated, a surface aquifer model was developed for contaminant transport modelling in case the contaminated water level reaches the level of the surface aquifer. This also involved integration of the regional watershed around the mines in the model. The selected domain, for the groundwater and contaminant transport modelling, including the three shafts (Leon II, III and IV) in Rydułtowy mine, as potential sources of mine water seepage into the surface aquifer, is presented below.



The surface aquifer model was implemented in the commercial software FEFLOW 7.1.

The Southern and Northern flow boundary conditions of the surface aquifer were assigned with a fixed hydraulic head of 9.5m and 1.5m, respectively. The groundwater flows from South to North in the model domain.



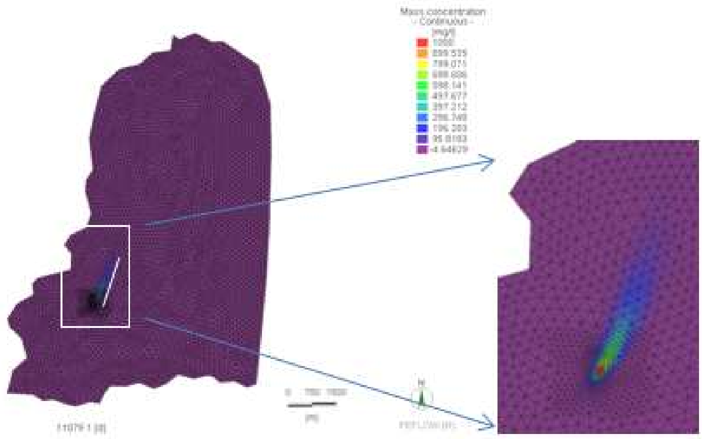
It has been reported previously that the surface aquifer (Holocene & Pleistocene clays and sands) has a filtration coefficient (hydraulic conductivity) of > 10^{-3} m/s (100 Darcy). This value was used for the horizontal hydraulic conductivity, and one tenth of which in the vertical direction. The other parameters, i.e. specific yield and the relevant transport properties are assumed based upon typical values found in the literature. Again, the two dispersion properties, the dispersivity parameter in flow direction (longitudinal dispersivity) and perpendicular to the flow (transverse dispersivity), have shown to have a transverse over longitudinal dispersivity ratio of 0.1.

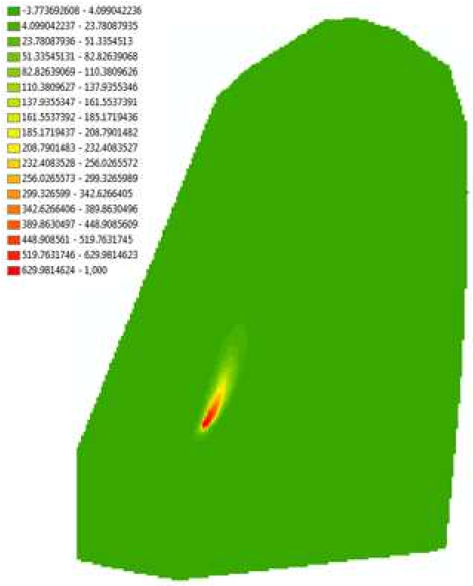
Flow properties		Transport properties	
Horizontal hydraulic conductivity, 10^{-5} m/s (Darcy)	100	Porosity	0.2
Vertical hydraulic conductivity, 10^{-5} m/s (Darcy)	10	Longitudinal dispersivity, m	70
Specific yield	0.12	Transverse dispersivity, m	7

Conservative contaminant transport modelling

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 1,500m in 30 years, and further to around 2,000m in 50 years. The simulation results after (a) 30 and (b) 50 years are seen below. GIS raster files were prepared in ArcMap accordingly to show the contaminant transport over the simulated period.





Reactive transport modelling

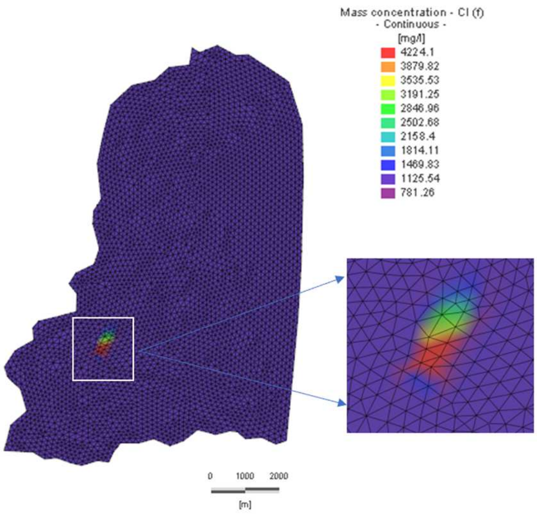
The first stage solute transport modelling described above assumed that the contaminants were conserved, i.e. there were no chemical reactions between the transported contaminant(s) and surface aquifer water. Next, multispecies solute reactive transport simulation to represent processes related to acid mine drainage were carried out to simulate the fate of the groundwater reactive contaminants. This was achieved by coupling PHREEQC and FEFLOW, carried out through the piChem plugin for FEFLOW.

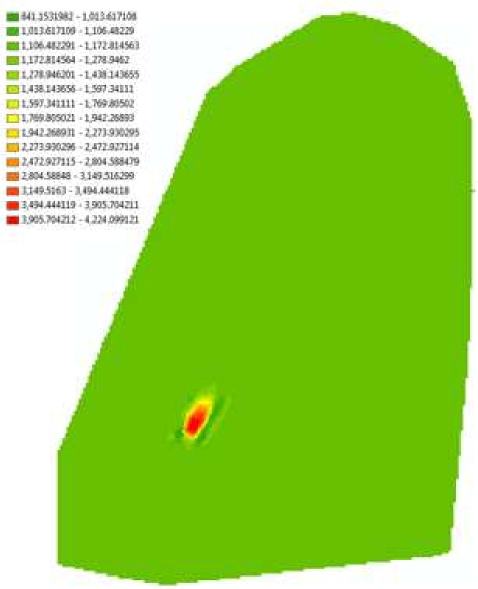
The reactive transport modelling reported here focused on the contaminants Cl, SO_4, Fe and Mn, which are the typical acid mine drainage components, as they are being transported in the surface aquifer. As in the solute transport modelling, a fixed contaminant concentration boundary condition of 1,000 mg/lt was also defined for all the species at the mine shaft location.

A PHREEQC input file for the boundary condition (bc_amd.phr) was used to describe the reactions related to the formation of the acid mine drainage, defining the component concentrations at the associated boundary as result of PHREEQC reaction calculation.

Then, for the inflowing boundary condition, it was assumed that the water composition is in equilibrium with the surface water solution of the corresponding geochemical domain. The geochemical characteristics of the watershed domain are relevant as the initial conditions for the reaction; thus a PHREEQC input file for both inflow boundary and initial conditions (domain.phr) was assigned based on the surface water composition for the sampling locations PS1, PS5 and PS6.

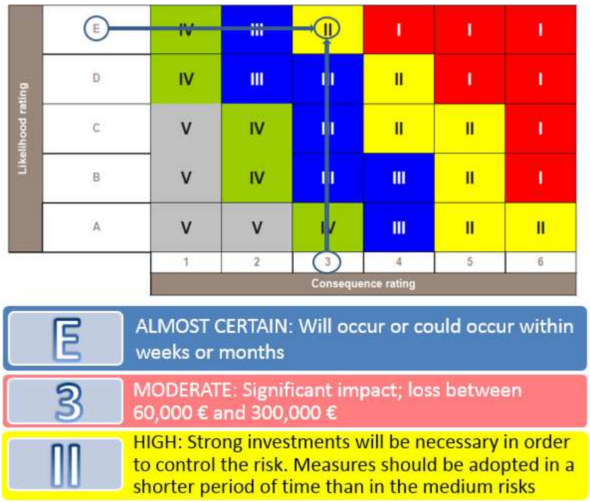
Reaction steps were calculated for every transport step, at 30 and 50 years. The simulation results showed that the contaminants, Cl, SO_4 and Mn, had adverse effects in the shaft location, in terms of irrigation and drinking purposes for the first year. The contaminants would be transported, and diluted along the way throughout the 30 and 50 years, with no effects along the pathway. The results for the contaminants (a) Cl at 30 years, (b) SO4 at 50 years and (c) Mn at 50 years, together with the corresponding GIS raster maps, are presented below.



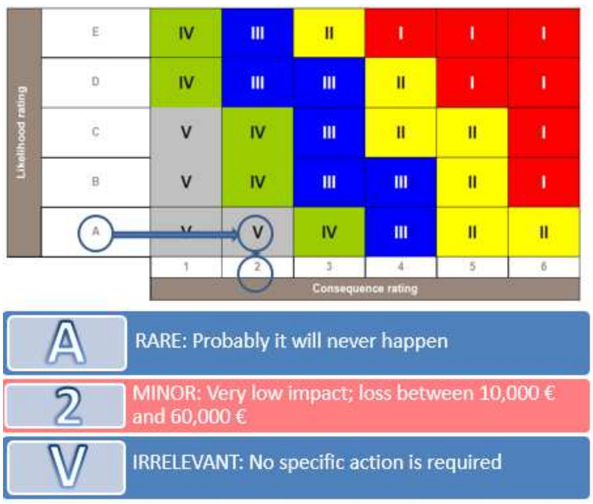


Risk assessment: Risk evaluation

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 proposed 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.



As the contaminants are diluted along the pathway over 30 and 50 years, the likelihood can be rated as "A"; which means that any adverse effect probably will never happen and therefore the impact and risk are very low and no specific action is required.



Risk assessment: Proposed treatments

Passive in-situ groundwater remediation using permeable reactive barriers (PRBs) 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 immobilise 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 immobilised 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.

The mechanisms involved in the reactive zone may include chemical oxidation/reduction reactions, precipitation, sorption, and biodegradation. It can be concluded that the most effective solution would be inventing in a pre-treatment zone of PRBs.

There are two basic types of PRBs: funnel-and-gate, where the contaminated groundwater is directed to a permeable reactive zone (the “gate”) by low permeability barriers, such as cut-off walls (the “funnel”); and continuous trench (wall), where the reactive treatment zone is placed in the subsurface across the complete width of the contaminant plume.

Of the two types of PRB systems, the funnel-and-gate system shows the greatest promise for cost-effective remediation of plumes, due to the large amount of reactive material required for a continuous trench.

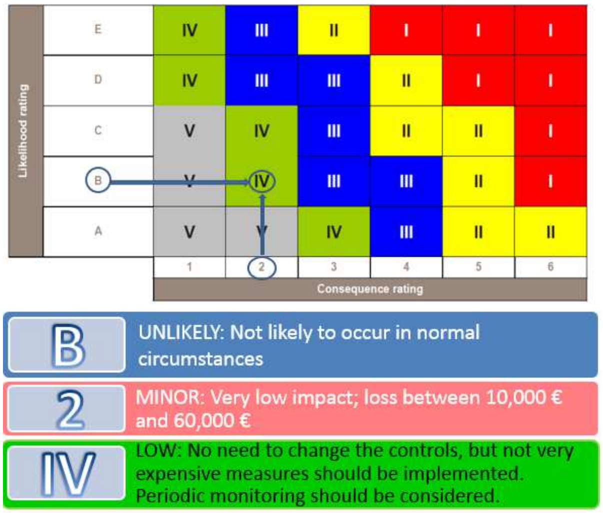
One of the most important factors in the investment process in the total capital and operating costs would be the reactive materials cost. PRBs have a favorable cost/benefit ratio compared to traditional (mostly pump-and-treat) systems used for groundwater remediation. This is true for both capital and 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 million.

Risk assessment: Performance forecast

The treatment option, as introduced, will aim to minimise the risks and the probability of any adverse effect associated with Cl, SO_4 and Mn. Hence, both the likelihood and the consequences ranking will be reduced.

Likelihood will be reduced to a "B", as it will be unlikely that the chemical pollution occurs in normal circumstances, and the impact will be very low, with losses between 10,000 and 60,000 €.



Thus, although there will be no need to change the controls, regular monitoring needs to be considered.

Economic evaluation: Cost evaluation

PRBs have a favorable cost/benefit ratio compared to traditional (mostly pump-and-treat) systems used for groundwater remediation.

For example, a PRB system could cost up to 450,000 €, versus the cost for a pump and treat remediation, reaching up to 6.3 million €.

There are no additional operation and maintenance cost associated with this system. So cost can be estimated in:

PRB system = 450,000 €

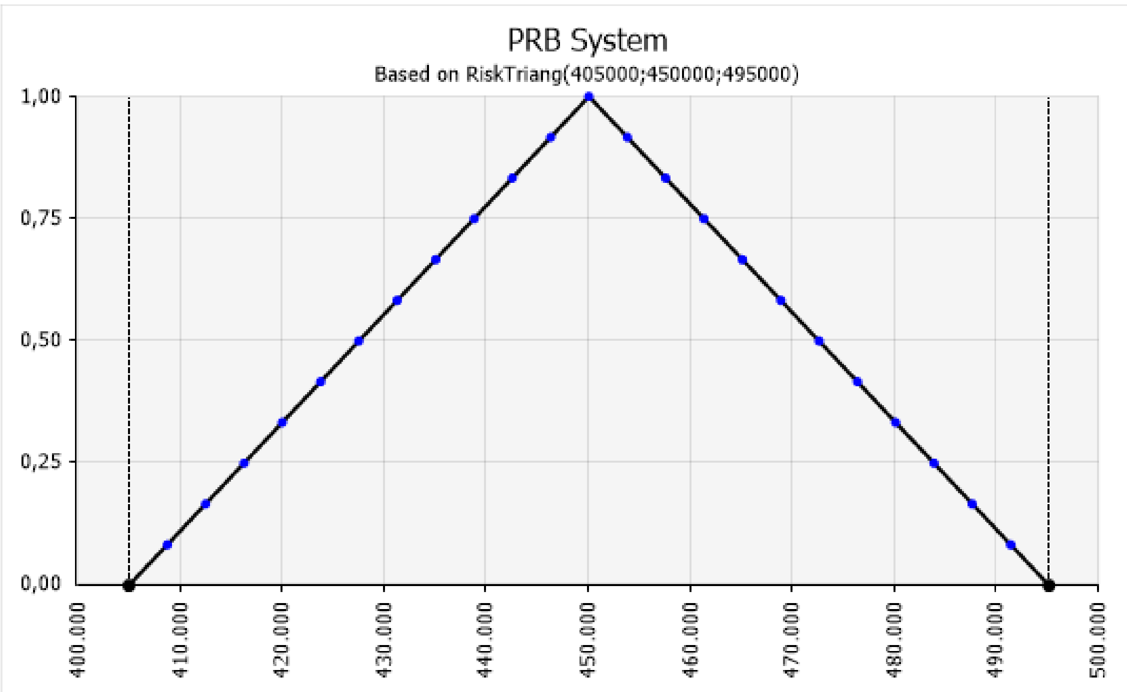
Economic evaluation: Financial provision

The Net Present Value in order to determine the financial provisions required for closure and post-closure regarding groundwater risks will be:

NPV = - 450,000 €

Economic evaluation: Uncertainty analysis

The PRB system will be modelled by means of a triangular function with parameters varying a 10% up and down, in order to represent possible variations in the investment cost, as presented below:



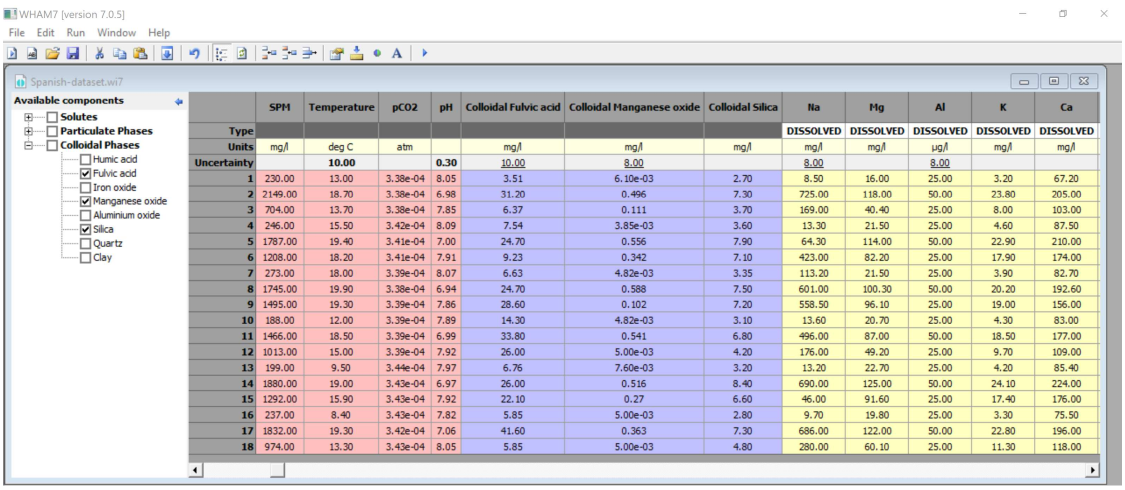
Model: Conceptual model

The Windermere Humic Aqueous Model (WHAM7) was used to model the discharged water quality (or surface water quality) at/around Rydułtowy-Anna Mining Complex in Poland. 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 (Cl^-, SO_4^{2-}, 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.

In MERIDA, 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.

WHAM7 uses three types of data files: input files, which define the chemical composition of a system or systems; solute databases, which define the solutes that may be simulated, and the equilibrium constants and enthalpies of formation of solution complexes and precipitates; and phase databases, which include the parameters describing ion binding to the available binding phases. The input file is displayed in a spreadsheet-style format. Each row represents one chemical problem, with concentrations of solutes and colloidal/particulate phases to the input file.



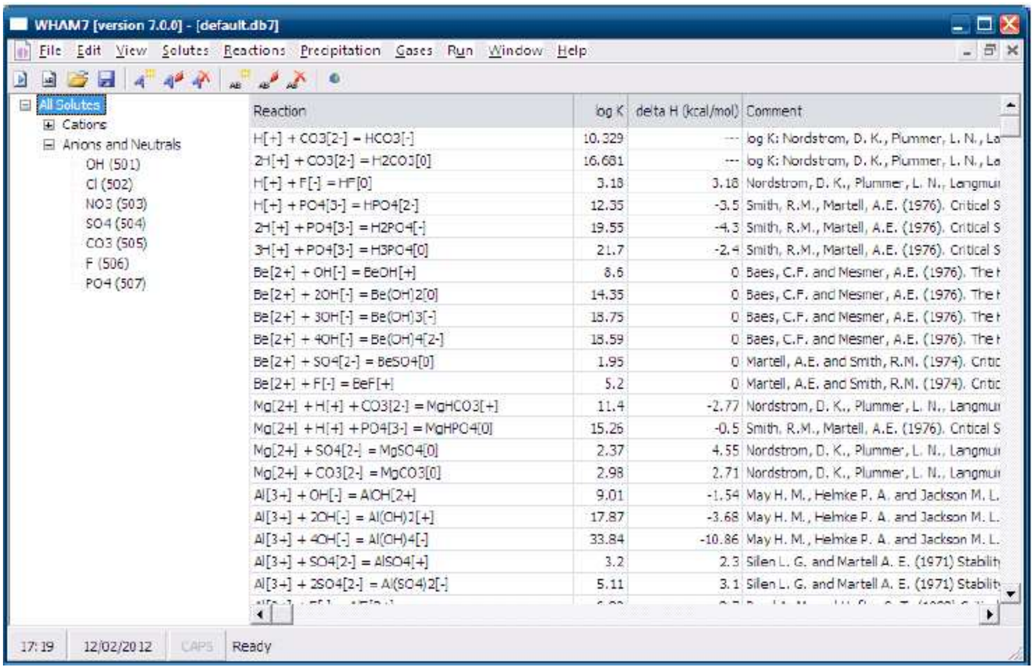
	SPM	Temperature	pCO2	pH	Colloidal Fulvic acid	Colloidal Manganese oxide	Colloidal Silica	Na	Mg	Al	K	Ca
Type								DISSOLVED	DISSOLVED	DISSOLVED	DISSOLVED	DISSOLVED
Units	mg/l	deg C	atm		mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mg/l	mg/l
Uncertainty		10.00		0.30	10.00	8.00		8.00		8.00		
1	230.00	13.00	3.38e-04	8.05	3.51	6.10e-03	2.70	8.50	16.00	25.00	3.20	67.20
2	2149.00	18.70	3.38e-04	6.98	31.20	0.496	7.30	725.00	118.00	50.00	23.80	205.00
3	704.00	13.70	3.38e-04	7.85	6.37	0.111	3.70	169.00	40.40	25.00	8.00	103.00
4	246.00	15.50	3.42e-04	8.09	7.54	3.85e-03	3.60	13.30	21.50	25.00	4.60	87.50
5	1787.00	19.40	3.41e-04	7.00	24.70	0.556	7.90	64.30	114.00	50.00	22.90	210.00
6	1208.00	18.20	3.41e-04	7.91	9.23	0.342	7.10	423.00	82.20	25.00	17.90	174.00
7	273.00	18.00	3.39e-04	8.07	6.63	4.82e-03	3.35	113.20	21.50	25.00	3.90	82.70
8	1745.00	19.90	3.38e-04	6.94	24.70	0.588	7.50	601.00	100.30	50.00	20.20	192.60
9	1495.00	19.30	3.39e-04	7.86	28.60	0.102	7.20	558.50	96.10	25.00	19.00	156.00
10	188.00	12.00	3.39e-04	7.89	14.30	4.82e-03	3.10	13.60	20.70	25.00	4.30	83.00
11	1466.00	18.50	3.39e-04	6.99	33.80	0.541	6.80	496.00	87.00	50.00	18.50	177.00
12	1013.00	15.00	3.39e-04	7.92	26.00	5.00e-03	4.20	176.00	49.20	25.00	9.70	109.00
13	199.00	9.50	3.44e-04	7.97	6.76	7.60e-03	3.20	13.20	22.70	25.00	4.20	85.40
14	1880.00	19.00	3.43e-04	6.97	26.00	0.516	8.40	690.00	125.00	50.00	24.10	224.00
15	1292.00	15.90	3.43e-04	7.92	22.10	0.27	6.60	46.00	91.60	25.00	17.40	176.00
16	237.00	8.40	3.43e-04	7.82	5.85	5.00e-03	2.80	9.70	19.80	25.00	3.30	75.50
17	1832.00	19.30	3.42e-04	7.06	41.60	0.363	7.30	686.00	122.00	50.00	22.80	196.00
18	974.00	13.30	3.43e-04	8.05	5.85	5.00e-03	4.80	280.00	60.10	25.00	11.30	118.00

Model: Numerical model

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.

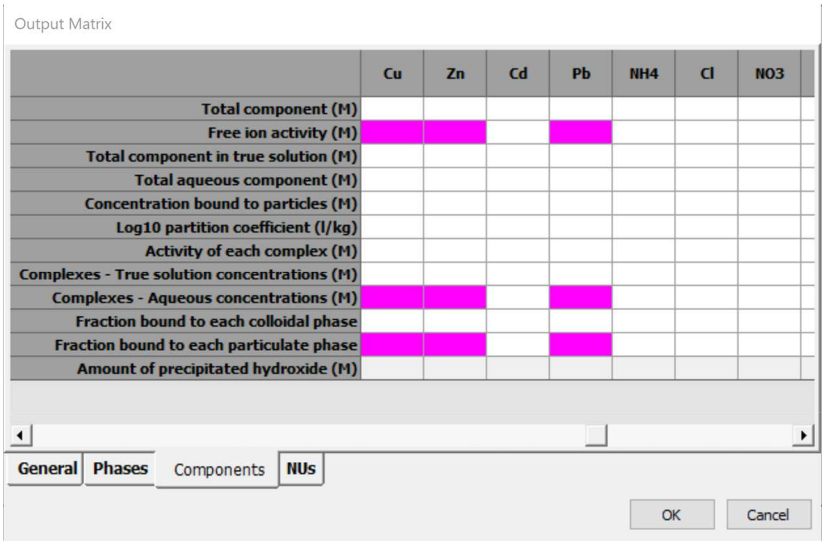


- Fe, Al and Mn have the tendency to oxidise, hydrolyse and/or precipitate in mine water environments. As pH levels for both mines were not low enough to prevent hydroxides from forming, all the iron and aluminium concentrations were assumed to precipitate as ferric and aluminium hydroxide, respectively; and manganese oxide (MnO_x) was considered 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.

Model: Simulation results

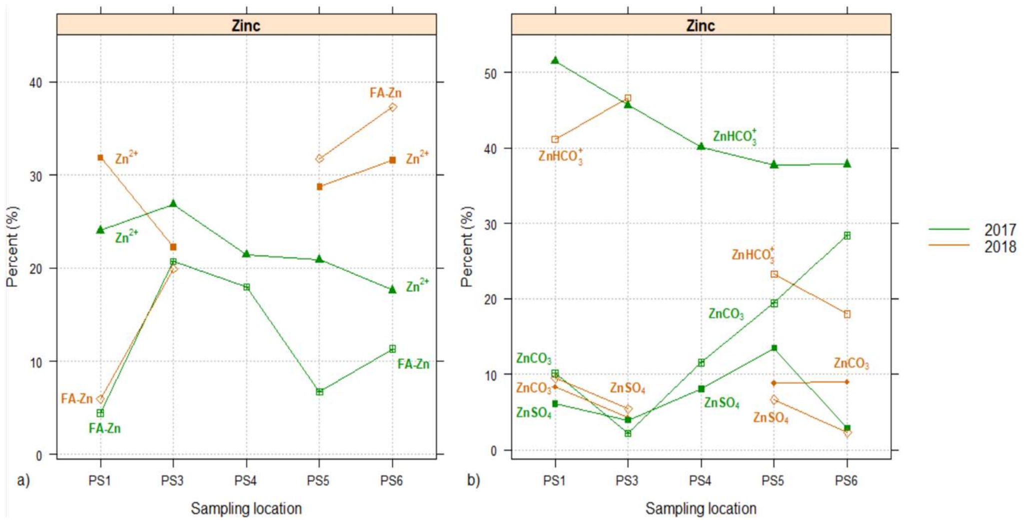
The output matrix of the model provides the component complex concentrations in the aqueous phase, the free ion activity and the fraction of each component for each of the colloidal phases.



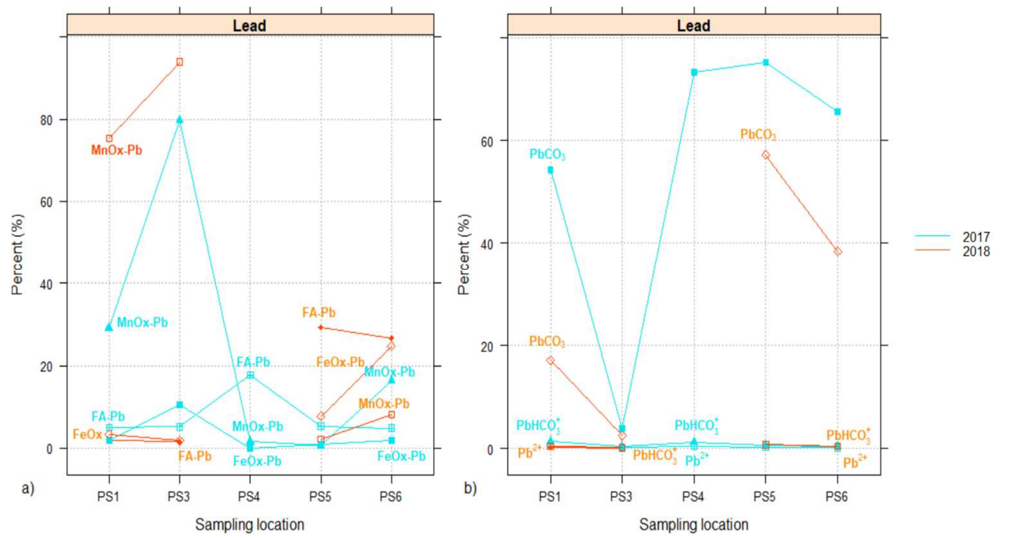
The results of the geochemical model provide the spatial/temporal species distribution for copper, zinc and lead. Selected examples for model results obtained are presented here. The water sampling locations at Anna mine are shown below.

For the Anna mine surface waters, the inorganic zinc speciation 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 sulphates, $ZnSO_4$ 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 mobilize the organic matter.



The geochemical modelling results for lead at Anna mine region surface 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 6), followed by iron (III) and manganese oxide complexes. The free Pb^{2+} ion was found at very low concentrations.



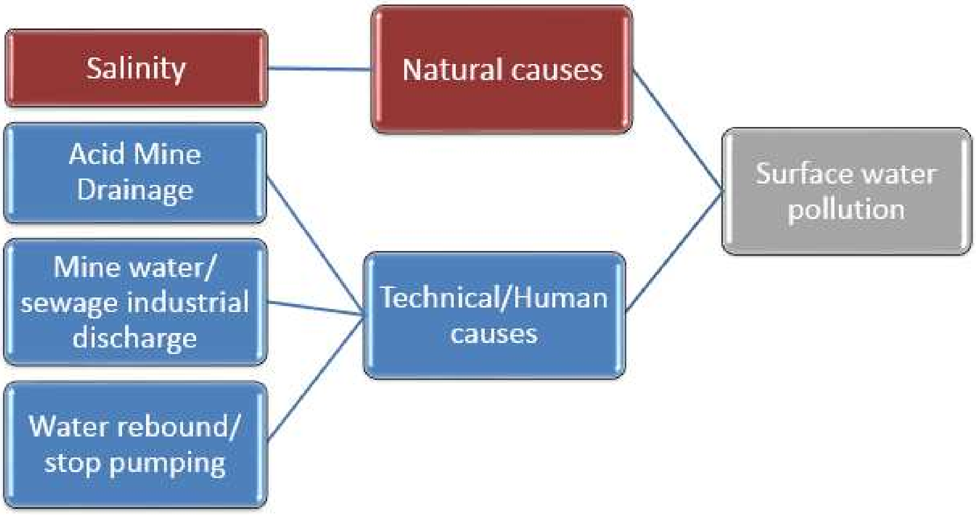
The geochemical speciation results for the free metal ions provided the necessary inputs for the bioavailability/ toxicity modelling used to perform the environmental risk assessment for surface waters around the abandoned coal mines studied.

Risk assessment: 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.

In the simplified "cause-and-effect" diagram shown here, illustrates the two main causal factors and the corresponding contributing factors that influence the level of risk associated with the surface water quality.



In addition to the above factors, interaction/ communication with other mines could also lead to pollution of local surface waters, if the discharge point of the acid mine water is located in the surroundings of such other mines.

When analyzing the surface water risk, associated sub-effects should also be considered in order to devise an efficient risk management plan.

According to the "source-pathway-receptor" elements concerning the risk posed by mine water, 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 assessment: Risk analysis

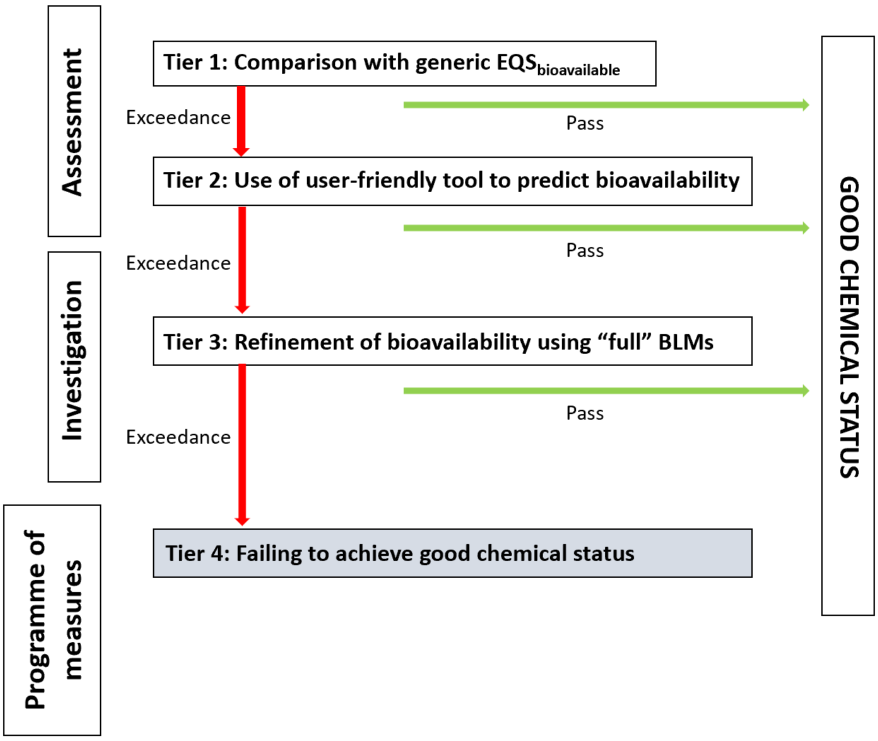
To assess the risk associated with surface water discharge, the bioavailable metal concentration was analysed including exposure and effect assessment steps. The assessment of exposure considers the concentration of the substances present in the environment. Subsequently, the effects assessment defines the extent that target organisms may be exposed to the contaminant.

The exposure assessment step 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). This is based on the analysed samples and measured discharge water composition.

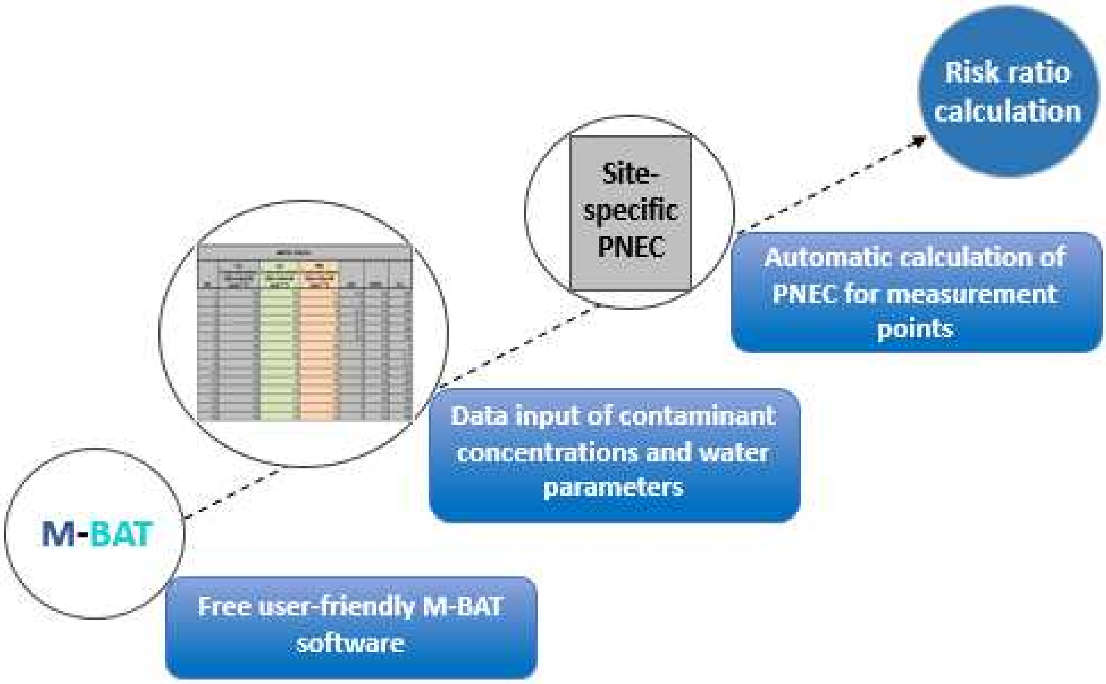
The effect assessment process is based on determining the ecotoxicological effects (NOEC) and is based on an appropriate method (probabilistic, algorithm, BLM), which allows the determination of the Predicted No Effect Concentration (PNEC). This value constitutes a protective concentration (a threshold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

User-friendly bioavailability tools approach: M-BAT for Cu, Zn, Pb and Mn

A flow diagram describing the possible stages of a tiered EQS compliance assessment for different metals (as a first step in the complete classic paradigm shown in the previous page) is shown below. These user-friendly screening tools mimic the BLM models and give an initial assessment of risks associated with metals in freshwater environments.



They require 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 approach to estimate a local PNEC and risk ratio is presented below.



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.

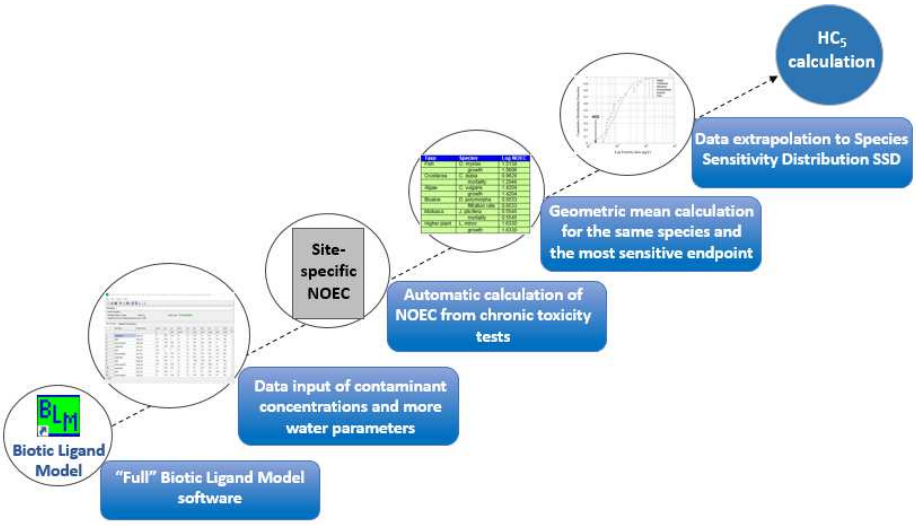
The analysed PNEC/bioavailable metal concentrations and corresponding risk ratio for the monitoring period studied are presented in the tables below.

		Results (Copper)			Results (Zinc)			Results (Manganese)			Results (Lead)		
Location	Sampling Date	PNEC Copper (µg l^{-1})	Bioavailable Copper (µg l^{-1})	Risk Ratio	PNEC Zinc (µg l^{-1})	Bioavailable Zinc (µg l^{-1})	Risk Ratio	PNEC Manganese (µg l^{-1})	Bioavailable Manganese (µg l^{-1})	Risk Ratio	PNEC Pb (µg l^{-1})	Bioavailable Pb (µg l^{-1})	Risk Ratio
PS1	2017	13.52	0.23	0.23	25.32	13.35	1.22	323.36	23.58	0.19	4.55	0.73	0.61
PS1	2018	14.44	0.14	0.14	25.91	7.57	0.69	323.36	133.13	1.08	4.80	0.63	0.52
PS3	2017	56.03	0.13	0.13	44.00	64.42	5.91	1253.75	23.55	0.19	16.80	0.36	0.30
PS3	2018	60.70	0.03	0.03	56.55	10.02	0.92	701.43	27.36	0.22	20.40	0.15	0.12
PS4	2017	12.27	0.41	0.41	25.53	20.92	1.92	266.45	1.66	0.01	4.55	1.32	1.10
PS5	2017	19.66	0.25	0.25	38.92	14.00	1.28	149.07	2.48	0.02	9.36	0.64	0.53
PS5	2018	27.81	0.05	0.05	42.92	2.54	0.23	219.55	0.84	0.01	10.56	0.28	0.24
PS6	2017	10.38	0.29	0.29	29.40	6.67	0.61	123.00	50.00	0.41	6.00	0.60	0.50
PS6	2018	16.72	0.39	0.39	31.77	17.50	1.61	123.00	3.50	0.03	6.96	0.43	0.36

At Anna mine (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.

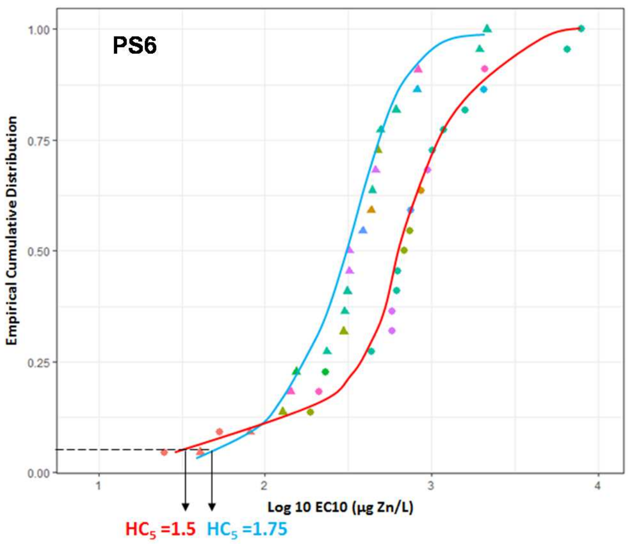
Probabilistic approach: Cu, Zn and Pb

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 Sensitivity Distribution function. The steps for the PNEC calculation based on the probabilistic approach are shown below.



Using the Species Sensitivity Distribution, the 5th percentile value is then specified (HC_5-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 (Anna mine) is presented below as an example.



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 HC_5 concentration of the heavy metals. The outcomes from the exposure (metal concentration) and effect assessment (HC_5-SSDs) are integrated in 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).

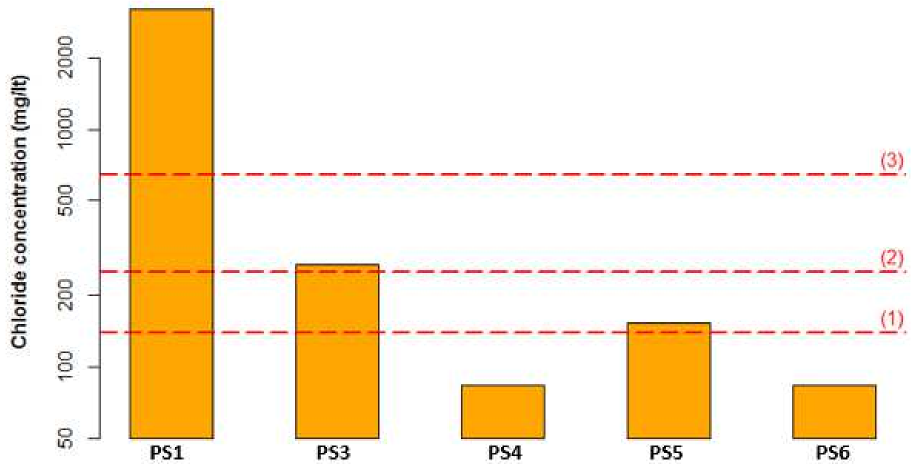
However, the highest zinc index at Anna mine occurred at the locations of purified rainwater discharge from Leon IV shaft (PS6 with a ratio at 1.01) and industrial sewage discharge to Syrynka stream at Ryszard point (PS4 with a ratio of 0.8). Mine water discharge to Nacyna river (PS1) had an elevated 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.

PNEC/EQS comparison approach: Fe, Cl and SO_4

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.

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

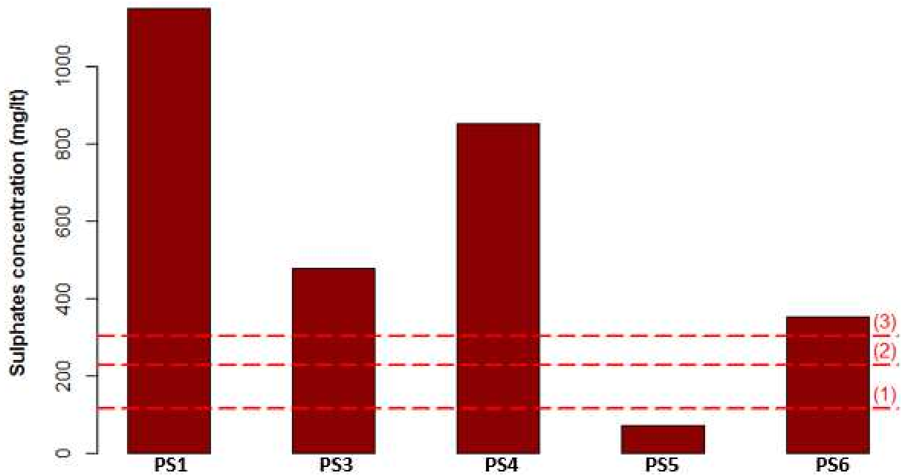
For Anna mine, only location PS1 of mine water discharge and PS3 of industrial sewage discharge, with concentrations 49 µg/lt and 160 µg/lt respectively, failed to reach the PNEC short-term (PS1) and long-term (PS3). High levels of chlorides can also make it difficult to achieve good or moderate ecological status in rivers. Chloride concentrations for different discharge locations at Anna mine and the corresponding quality standards are shown below.



(1) PNEC long-term: 139mg/lt (MANAGER probabilistic approach from SSDs)
(2) Drinking standard: 250mg/lt (WHO and US.EPA Ambient Quality Criteria)
(3) PNEC short-term: 644mg/lt (MANAGER probabilistic approach from SSDs)

At Anna mine, the majority of the samples exceeded the threshold values for Chlorides, which may induce indirect effects on the aquatic ecosystems and drinking water quality.

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.



(1) *PNEC long-term: 115mg/lt (TGD deterministic approach based on 3 species)*
(2) *Drinking standard: 250mg/lt (WHO and US.EPA Ambient Quality Criteria)*
(3) *PNEC short-term: 303mg/lt (MANAGER probabilistic approach from SSDs)*

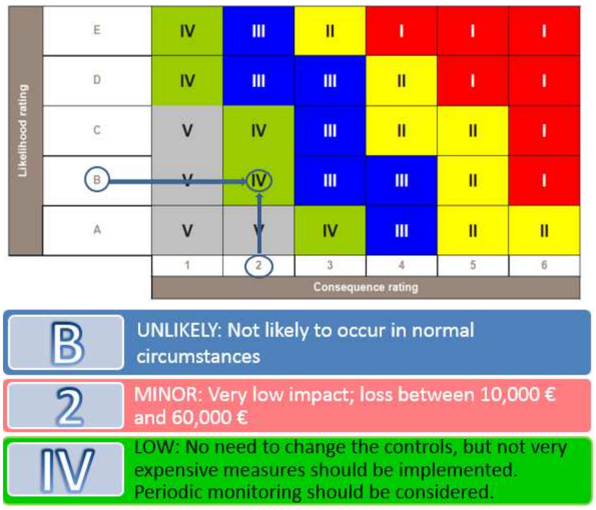
Similar to chlorides, the majority of samples at Anna mine exceeded the sulphates thresholds values in terms of both the no-effect concentration for the aquatic ecosystem and the drinking water standards.

Risk assessment: Risk evaluation

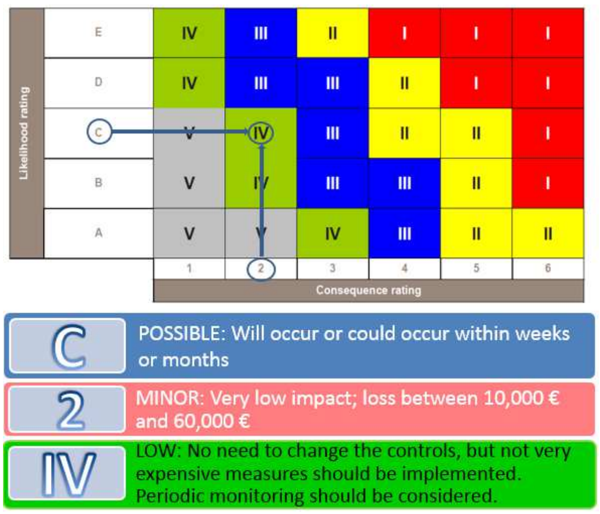
The chemical and aquatic toxicity risk analysis results were used to produce a risk index for each particular contaminant, allowing comparing the results with established risk criteria and determining the consequence of any adverse effect and when additional action is required.

The results obtained are presented below. For Anna mine, 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 Anna mine.

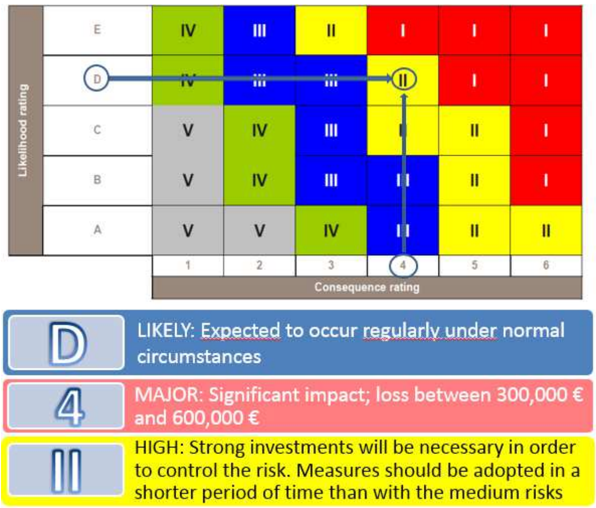
However, for PS4 (risk index= 0.78) and PS6 (risk index= 1.0) for zinc and for PS1 (risk index= 1.0) for manganese at Anna mine, there is a likelihood for potential risk to occur if conditions change; and although the risk is low, occasional monitoring should continue.



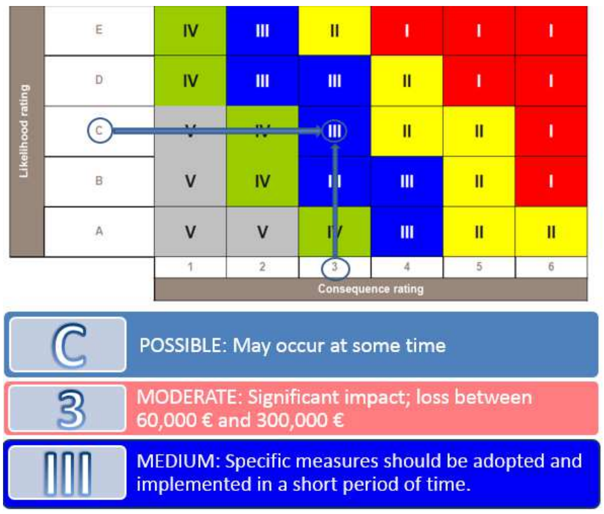
Although there is no potential risk associated with heavy metals, there is risk associated with iron concentrations. Below is the risk matrix for Anna mine.



Similarly, for chlorides, the risk matrix for PS1 (mine water discharge) at Anna mine is presented below.



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



Finally, sulphates risk matrix is 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, and equal to the risk matrix for chlorides at PS1.

Risk assessment: Proposed treatments

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

It is necessary to take steps to monitor regularly the concentrations of these substances in the surface water following mine closure.

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 is considered a better approach for net alkaline waters. It is the simplest type of passive treatment and is used to treat mildly acidic or net alkaline waters containing elevated Fe concentrations.

Its primary function 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.

A typical aerobic wetland system is a shallow, surface flow wetland vegetated with aquatic plants such as cattails. They translocate O_2 to the subsurface through their roots, which aids metal oxidation; but also help to prevent channelization of the waters flowing through the wetland, slowing water velocities and aiding solid-phase metal removal via sedimentation.

The AMD flows horizontally through the ponds and over substrate and the oxidation reactions precipitate the oxides and hydroxides. The depression that holds the wetland may or may not be lined with a synthetic or clay barrier.

Depending on landscape conditions, the lining can be intended to either to keep treatment waters from draining out through the depression's base or to prevent environmental waters from moving into the system and thus diluting the waters to be treated.

Aerobic wetlands have been shown to be an efficient and cost-effective remediation method, and have been used in 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

The Cost Effective Sulphates Removal (CESR) process removes high concentrations of sulphates through addition of hydrated lime ($Ca(OH)_2$), which precipitates calcium sulphates.

The CESR process essentially consists of four steps:

1. Initial precipitation of sulphate as gypsum
2. Precipitation of metals as hydroxides in a gypsum matrix
3. Additional sulphate removal via ettringite precipitation
4. pH reduction using re-carbonation.

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).

Capital and operating costs will depend upon the flow rate, the sulphates concentration to be removed, the final sulphates concentration to be achieved, and other water quality parameters (e.g., sodium and chloride concentrations).

Operating costs are typically 1.14 € to 2.28 € per 1,000 l treated for removal of sulphates, based on reagent consumption. For example, the reagent cost would be approximately 1.14 € per 1,000 l 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

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.

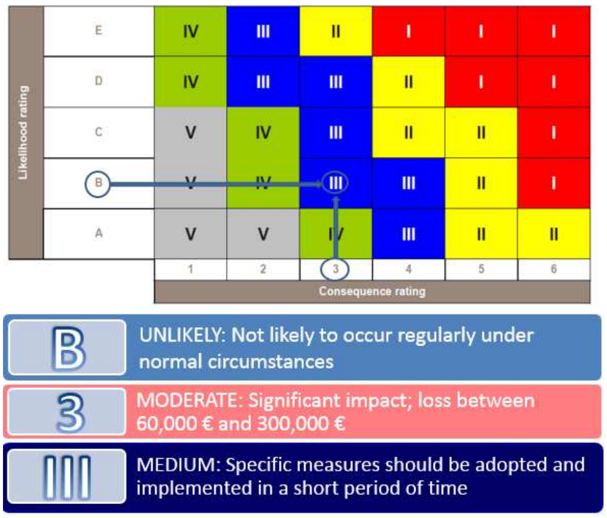
A Mechanical Vapor Compression system not only greatly reduces energy costs, but also reduces the CO_2 footprint, as it permits the continuous recycling of this energy by compressing the steam.

Treatment capacities could range from 1,150-15,000 l/h, with a typical operating cost of 2.4-4.8 € per 1,000 liters of condensate.

Risk assessment: Performance forecast

The different treatment options, as introduced, will aim to minimise the risks and the probability of any adverse effect associated with the chemical parameters. Hence, both the likelihood and the consequences ranking will be reduced.

Solutions, especially for iron, need to target to lower the likelihood ranking from "E" to "B" and therefore the consequences to be reduced from "4" to "3".



Regular monitoring, especially of the contaminants having a high level of risk, needs to be considered, whether water treatment has to be continued.

Economic evaluation: Cost evaluation

Risk associated with iron

To treat the risk associated with iron, we will select the cheapest method, the aerobic wetland. Taken into consideration that the terrains to be used should belong to the mining company and the amount of water that is discharged, the cost can be estimated in:

Aerobic wetlands = 140,000 €

A small maintenance of the area during the five years that according to the calculations is expected to be needed, can be estimated in:

Yearly wetlands maintenance = 1,800 € x 12 = 21,600 €

Risk associated with sulphates

In order to treat the risk associated with sulphates, 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, has been selected.

Operating costs are typically around 0.73 to 1.5 € per 1,000 l treated for removal of 1,500 mg/l of sulphates, based on reagent consumption. The problem is that it is not feasible from the economic point of view to remove sulphates for the different discharge points. Moreover, the mining company is allowed to discharge water in the Nacyna River with 1,800 mg/l of sulphates, so there is nothing to do with sulphates.

Risk associated with chlorides

Relating the chlorides, the risk was rated again as high for PS1 mine water discharge and medium at PS3 industrial sewage discharge, thus strong investments will be necessary in order to control the risk in PS1, and specific measures should be adopted in PS3.

To fight against this risk, 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.

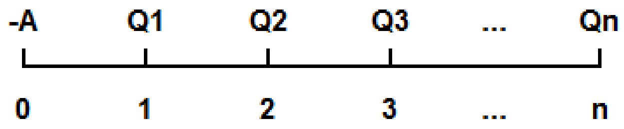
The equipment is compact and so the operational monitoring is simple, allowing effluent flows of up to 20 m^3/h to be treated in a single evaporator. Treatment capacities could range from 1,150-15,000 l/h, with a typical operating cost of 2.4 -4.8 € per 1,000 l of condensate

It has to be considered that this process will be necessary only during the first five years after the end of the flooding of the mines.

Nevertheless, we are facing the same question than with sulphates. It is not feasible from the economic point of view.

In addition, in this case the mining company is allowed to discharge water in the Nacyna River with 8,500 mg/l of chlorides, so there is nothing to do with that.

Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 140,000 €

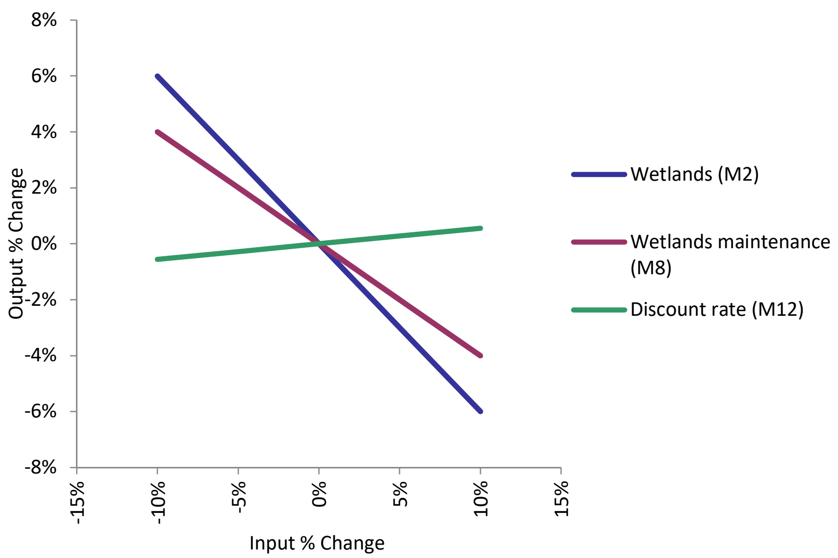
Q1, Q2, Q3, Q4, Q5 = - 21,600 €

k = 5%; n = 5

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 will be:

NPV = - 233.517 € €

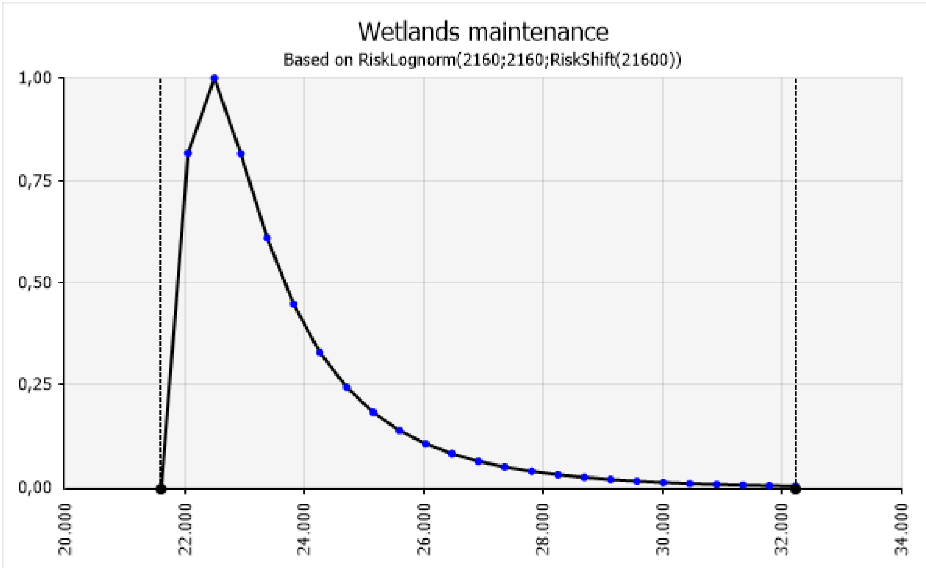
In order to estimate to which cost the MPV is more sensitive, a sensitive analysis was developed by means of allowing a ±10 % in every variable. The spider graph obtained was the following one:



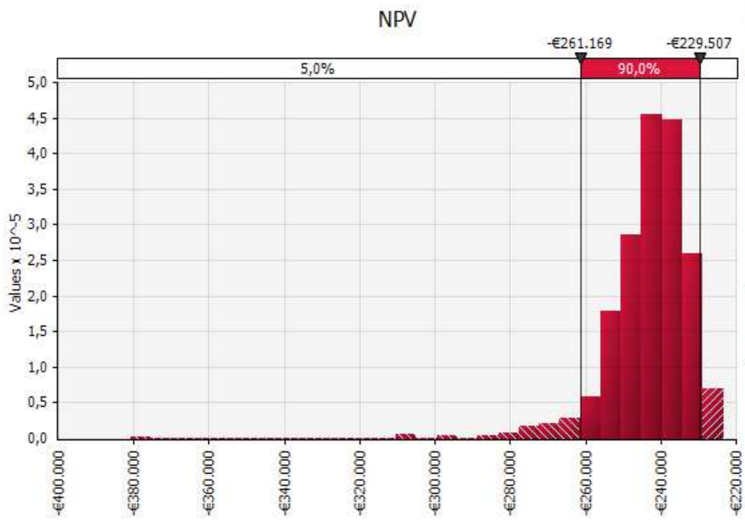
Economic evaluation: Uncertainty analysis

In this case, the main variable in this analysis are the wetlands construction, followed very closely by the maintenance costs, while the discount rate is almost irrelevant for the purposes of the sensitivity analysis.

In order to undergo an uncertainty analysis, we will model the yearly costs of the maintenance by means of a lognormal function, as it is one of the function that better models natural phenomena. This distribution will be centered in 21,600 and with a standard deviation of approximately 2,160. µ value will be 2,160 and σ value 2,160.



On the other hand, no possible variations of the discount rate will be considered, but the investment will be modelled by triangular functions with parameters varying a 10% up and down. Running the Monte Carlo analysis, the NPV will be the following one:

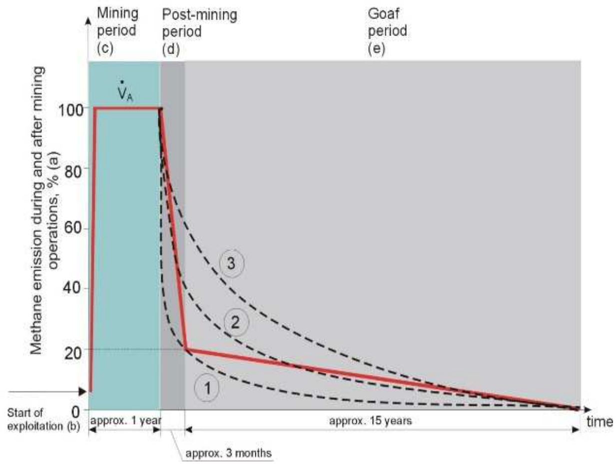


	NPV
Cell	NPV!C1
Minimum	-€380.931,00
Maximum	-€223.349,07
Mean	-€242.896,14
90% CI	± €591,41
Mode	-€244.706,88
Median	-€241.354,05
Std Dev	€11.359,52
Skewness	-3,1122
Kurtosis	28,5125
Values	1000
Errors	0
Filtered	0
Left X	-€261.169
Left P	5,0%
Right X	-€229.507
Right P	95,0%
Dif. X	€31.661,44
Dif. P	90,0%
1%	-€280.267,52

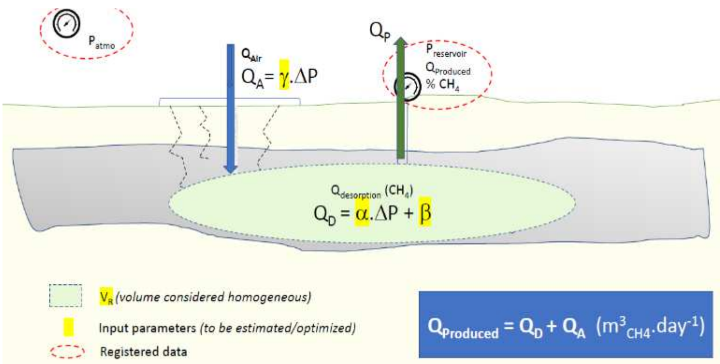
So the NPV distribution obtained has a mean of -242,896 €, a maximum of -223,349, a minimum of -380,931 and a standard deviation of 11,360 €.

Model: Conceptual model

As the main assumption, the model must include 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.



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.



The key parameter is a volume of emitted methane which can be assessed following the model of methane emission from panel goafs after finishing mining operations. In order to assess the amount of methane that is released from goafs a following formula is being used:

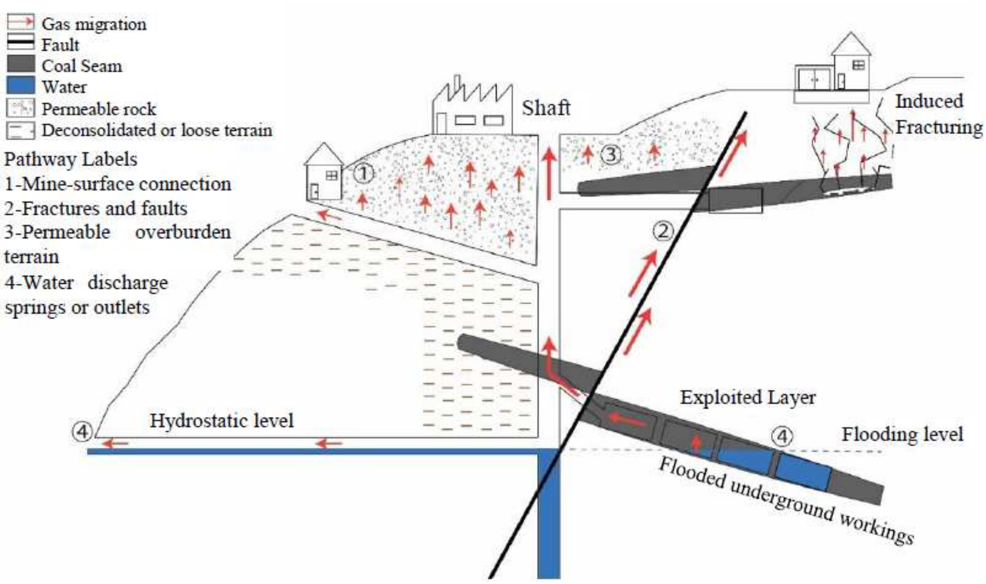
For Poland (where coal seams are rather horizontal or with small inclination):

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

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.

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.



Source: UNECE, (2019)

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 Cα 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.

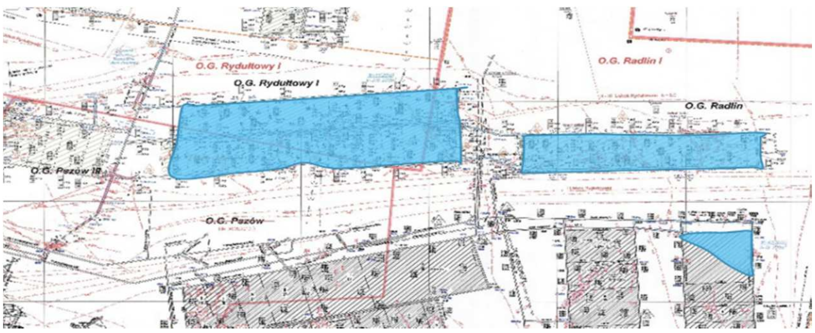
Model: Numerical model

It is expected that the numerical model will contain elements representing voids, such as liquidated galleries, shafts and goafs. The model also contains elements that affect the analyzed phenomenon, such as flooded coal seams and mine areas. Connections between mine areas and shafts allow water and gas to flow. These elements represent important gas migration paths to the surface layers and areas of mines bordering the abandoned mine.

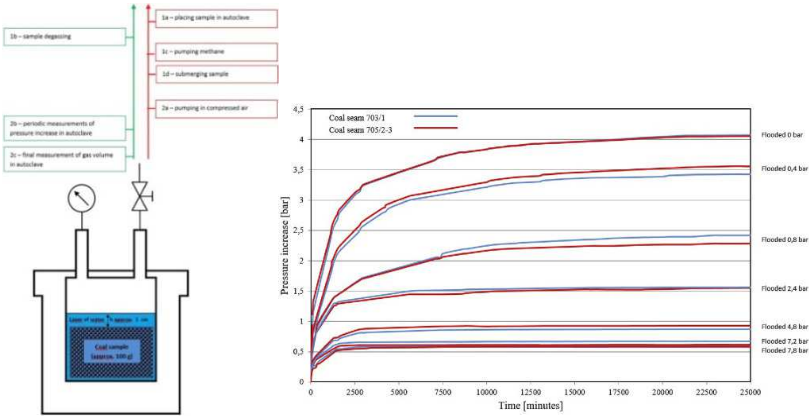
The physical laws that govern gas flow in the mine voids depend mainly on the processes of gravitational gas transport and pressure differential due to changes in atmospheric pressure and changes caused by the operating ventilation network of an active mine if it borders with a closed mine. For this purpose it is recommended to use a special software to model gas flow in the mine. Mine ventilation network simulators like Ventgaph software have been sucessfully used for mining operations. Based on one dimensional airflow approximation they provide a simple, easy to interpret representation of ventilation systems. Within the frames of MERIDA project this functionality has been extended to the period of abandonemet. At first the evolution of the emission of methane from goafs to the voids of a closed mine within sufficiently long period is to be foreseen.

Longwalls	J-12	G-2	R-14	J-11	G-1	R-16	R-17	R-15a	R-15	Total
End of mining operations	2008	2010	2009	2010	2012	2013	2014	2015	2017	
	Methane emission into goafs of longwalls in consecutive years [m³ CH₄/min]									
2017	0.64	0.55	0.71	0.26	0.71	0.72	1.10	0.37	4.04	9.10
2018	0.53	0.48	0.61	0.23	0.64	0.65	1.01	0.34	0.75	5.25
2019	0.43	0.41	0.51	0.19	0.57	0.59	0.92	0.31	0.70	4.63
2020	0.32	0.34	0.41	0.16	0.50	0.52	0.83	0.28	0.65	4.01
2021	0.21	0.27	0.31	0.13	0.43	0.46	0.73	0.25	0.59	3.39
2022	0.11	0.21	0.20	0.10	0.36	0.39	0.64	0.23	0.54	2.77
2023	-	0.14	0.10	0.06	0.29	0.33	0.55	0.20	0.48	2.15
2024	-	0.07	-	0.03	0.21	0.26	0,46	0.17	0.43	1.63
2025	-	-	-	-	0.14	0.20	0.37	0.14	0.38	1.22
2026	-	-	-	-	0.07	0.13	0.28	0.11	0.32	0.91
2027	-	-	-	-	-	0.07	0.18	0.08	0.27	0.60
2028	-	-	-	-	-	-	0.09	0.06	0.22	0.36
2029	-	-	-	-	-	-	-	0.03	0.16	0.19
2030	-	-	-	-	-	-	-	-	0.11	0.11
2031	-	-	-	-	-	-	-	-	0.05	0.05
2032	End of methane emission into goafs in seam 713/1-2									

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. 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.



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. For its determination it is necessary to carry out laboratory tests using autoclaves.



For extended and complicated systems of workings characterized by domination of length over the dimension of cross-section (shafts, galleries), a one-dimensional modeling is still feasible. Equations conforming to Kirchhoff's first and second laws were also developed. Pressure losses are proportional to the mass stream for the filtration Darcy flow and for turbulent the losses are proportional to the square of the mass flow. Hence in general the equations are non-linear and their solution is obtained by iteration methods.

Radon

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.

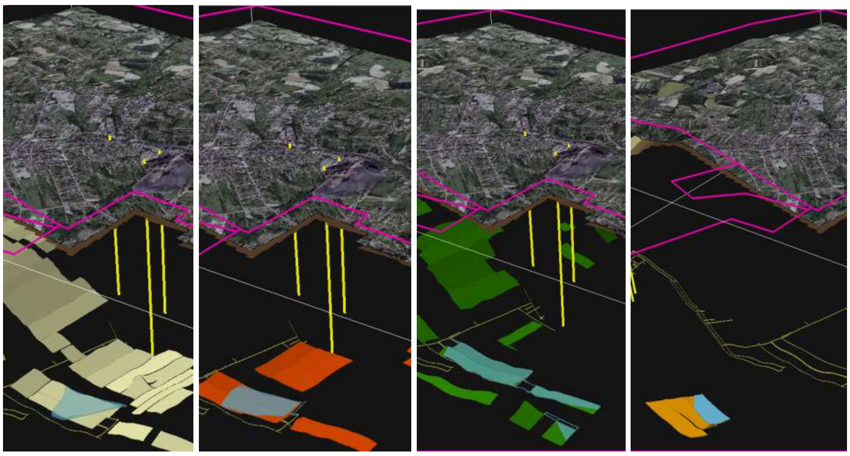
The distribution of the concentration of a given gas along a branch may be evaluated when gas sources are introduced, and the streams of gases are mixed at junctions. Hence, it is possible to obtain the profile of the concentration of the gas in the network and the properties of the stream reaching the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

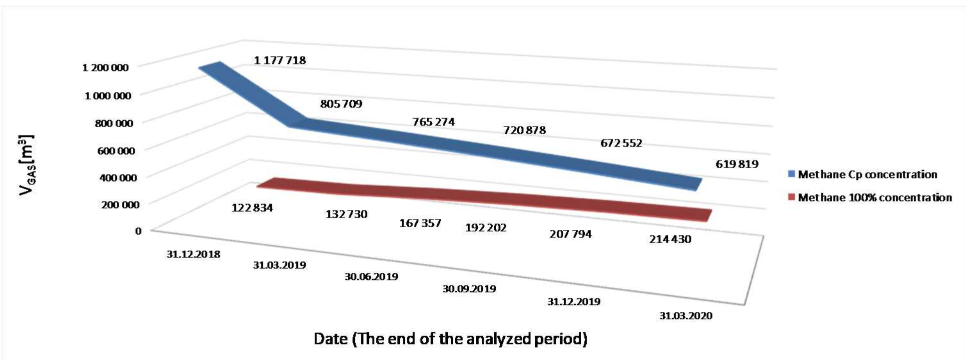
Model: Simulation results

The original purpose of those simulators was the flow in galleries and shafts, but may be extended to any flow path characterized by a flow rate. This concept has been used in the model of filtration flow in goafs applied in the VentGoaf module of the Ventgraph simulator. Initially the description did not consider the composition of the mine air, just the flow rate. Knowing the flow rates and the composition at the branch/path inlet one may solve equations of advection transport of admixed gases. Supplementing this description with gas sources and dependencies for mixing streams of gases in junctions leads to gas transport models, which make the Mine Ventilation Network Simulators useful for the analyses of migration of mine gases to the atmosphere. Another result of MERIDA was a development and implementation of the Ventgraph Radon module modelling radon exhalation, its radioactive decay and the losses during transport in the ventilation system of a mine. This software is a tool for prediction the radiation hazard in underground mines and at points of release of this gas to the atmosphere.

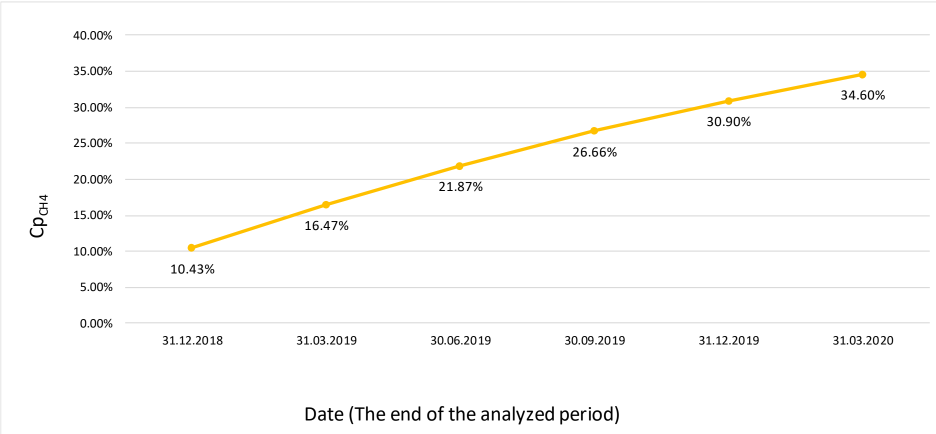
The results of the models allow to gain knowledge about the evolution of the gas hazard in the liquidated mine in the period from the start of closure process to the end of methane emissions from the goafs and stabilization of the risk level. First of all, the places of methane emission from goafs and the percentage of flooding these places with water were identified.



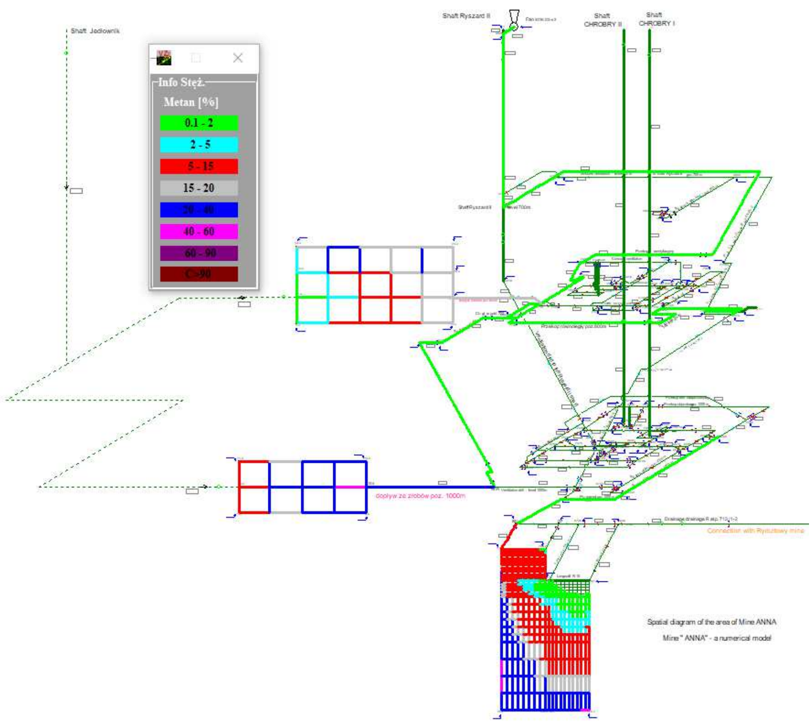
Secondly, comparing the calculated volume of gas evolved with the volume of voids allows for the assessment of the potential gas hazard.



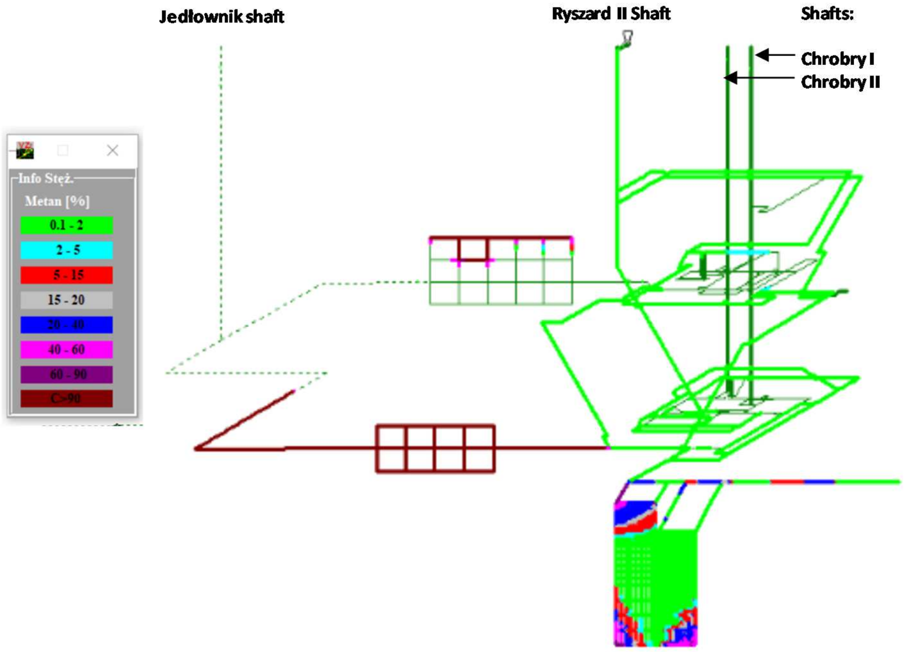
Finally, methane concentrations for individual periods of time in the mine voids treated as a reservoir are calculated.



After full identification of the parameters indicated above and analysis of the data correctness, the Ventgraph software can be used. It should start from getting or building a calibrated model of the ventilation system just prior to the beginning of abandonement. Then a set of simulations of gas migration from underground sources through non flooded system of voids towards atmosphere may be performed. For a given abandonement plan the effects of stepwise sealing of mining levels and regions followed with stoppage of ventilation and capping the shaft outlets and further process of flooding of the system of undeground voids can be modelled and subjected to a multi-varant analyses. 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 whole ongoing closure process the mine (starting from year 2017).

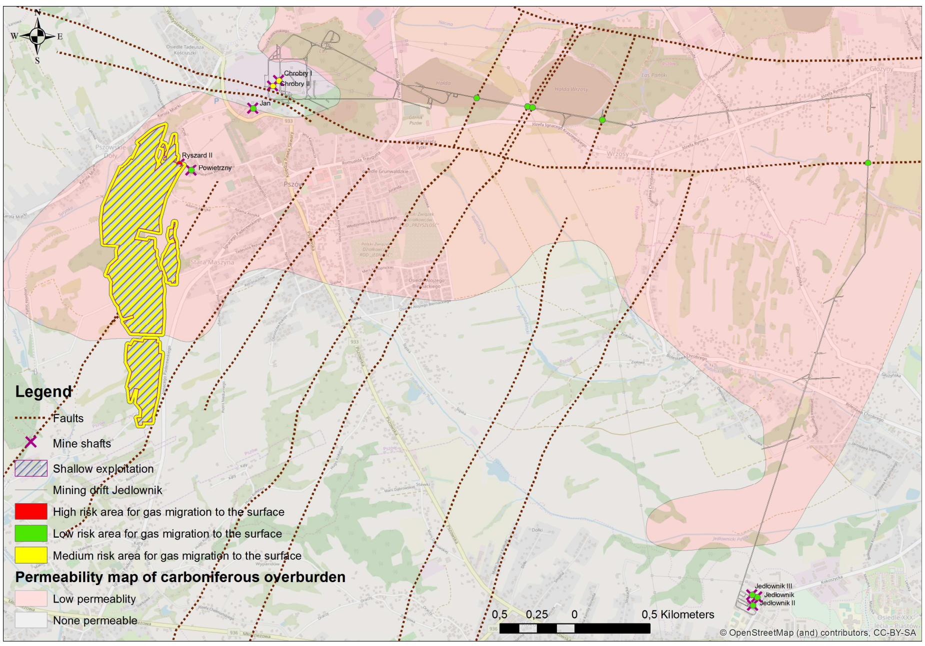


To its completion (year 2033).



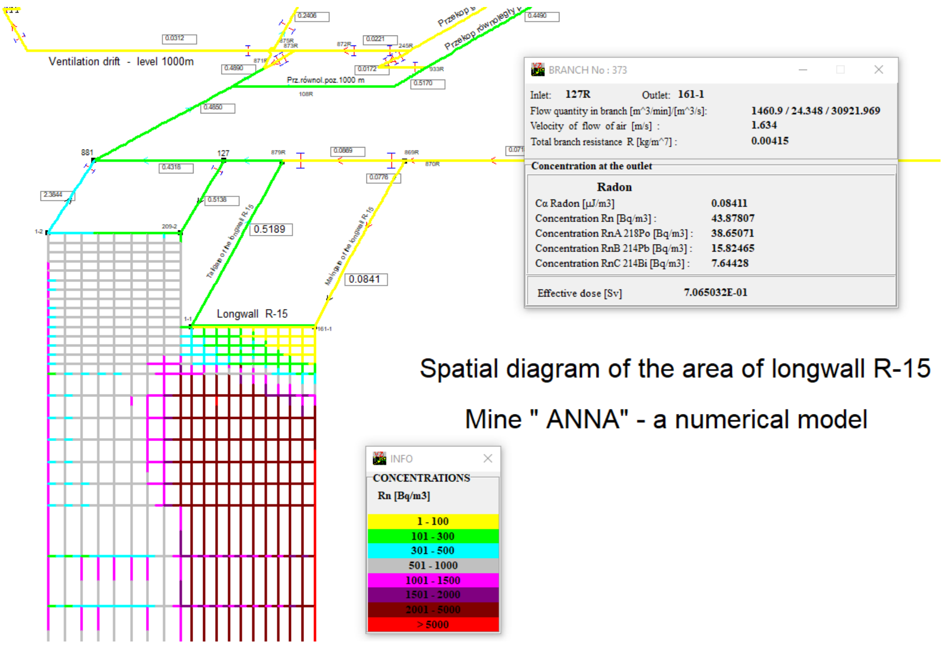
Results of gas hazard in a closed mine should be analyzed in terms of places of possible gas outflow to the surface. As the outcome of such case studies the recommendations on the extent and sequence of sealing off and floding galleries, shafts and goaf regions may be given. The final result of the model is a map of the area with identified areas where a risk of gas outflow possibly exists.

The map of the Anna mine area with identified areas where a risk of gas outflow possibly exists.

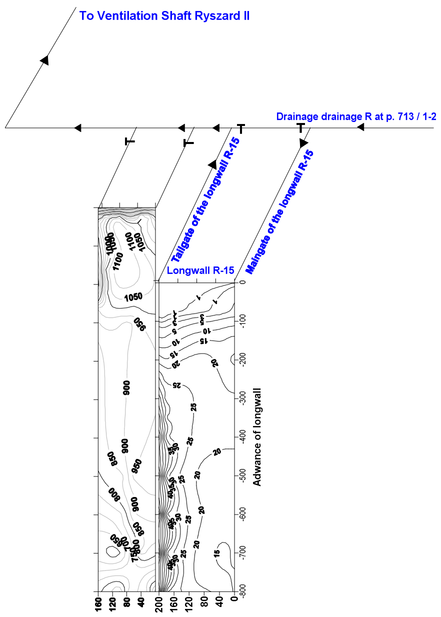


Radon

The calculated distributions of radon concentration is presented below 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 (Calpha), as calculated with the use of the VentGraph-Plus-module Radon programme.

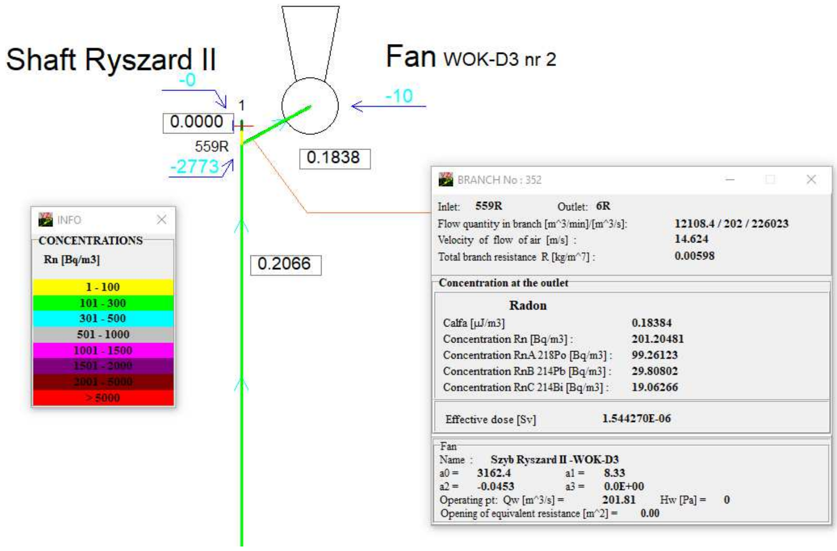


The calculated distribution for radon concentration considered the losses caused by diffusion and gravitational sedimentation for each heading and in the area of the goaf of longwall R-15 and the goaf of liquidated longwall R15a. The calculated distribution of radon concentration in these areas is shown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



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.

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 are as follows:



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).

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.

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 were 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. In Asturias only soil gas concentration was measured.

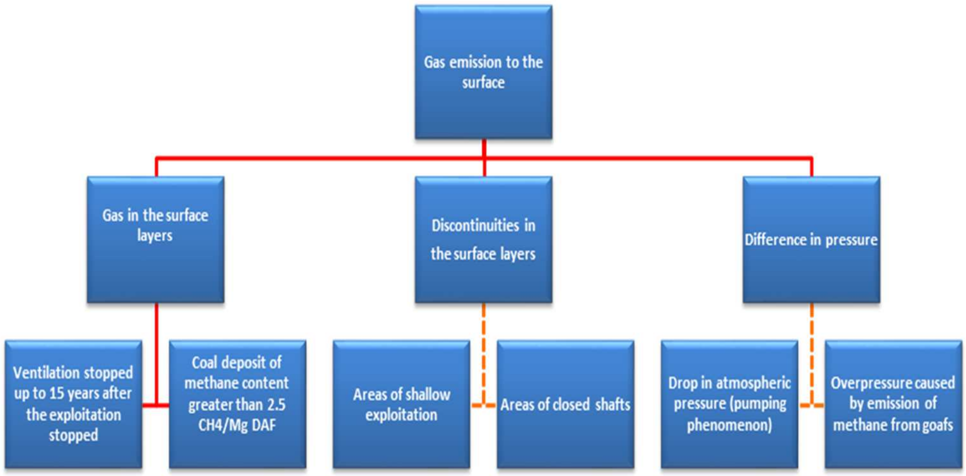
In most countries the uniform method for assessing the risk of radon penetrating from the underlying soil or bedrock, based on determining the radon index of the building site, proposed by Czech scientists, was implemented. Radon long-term monitoring, with use of nuclear track detectors is the appropriate technique to monitor the hazard in dwellings and workplaces.

Risk assessment: Risk identification (methane)

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.

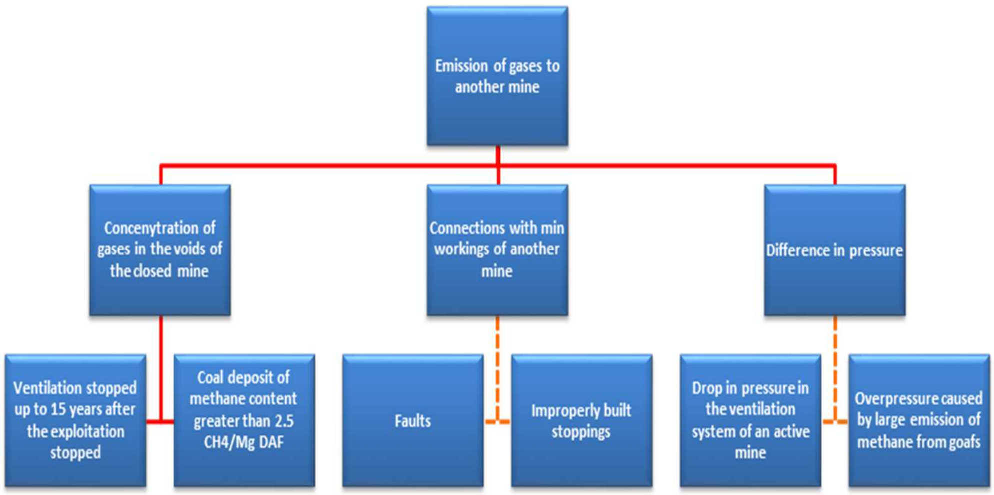
Hence, in a simplified way, the diagram below presents the dependence in form of branches of the fault tree with logic gates: "OR" (orange dashed line) and "END" (red solid lines).

The fault tree method is applied to analyse the risk of occurrence of unfavorable events (disasters, accidents, failures) as well as to analyse the course and circumstances of the events that have already occurred.



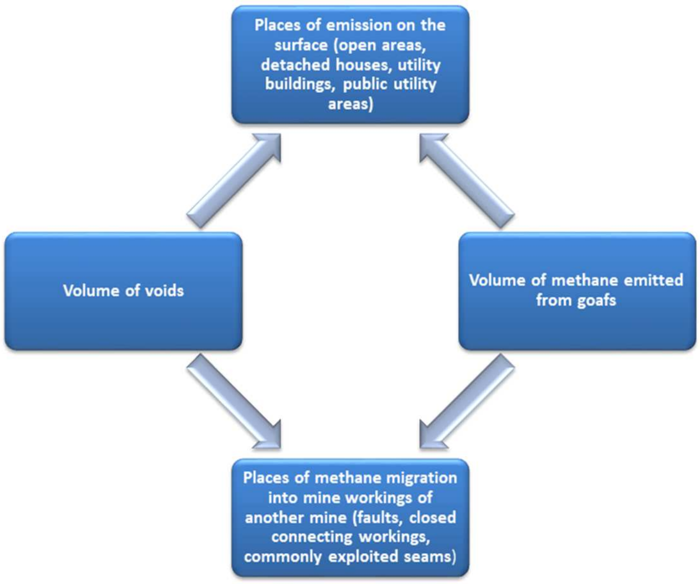
The dependences seen in the tree are the basic criterion determining whether to conduct further analysis – if none of the elements linked with red lines occur, there is no need to analyse the risk associated with the migration of gases to the surface.

The situation looks similar for the emission of gases to another mine and the tree for the risk is presented below.



If all the conditions linked with red lines occur, it is necessary to conduct an analysis following the cause-and-effect model based on standard IEC/ISO 31010, 2009 which was adopted within the MERIDA project.

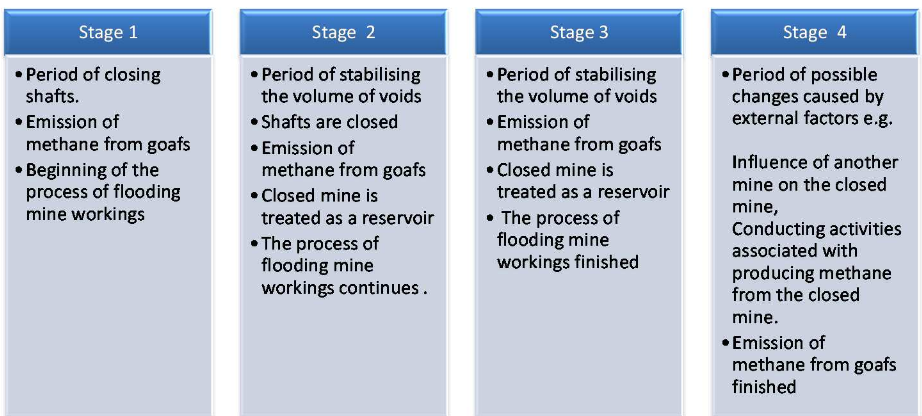
The factors influencing risk associated with gas hazard presented in the diagram below influence significantly the change in the level of risk associated with the migration of gases to the surface and to another mine.



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.

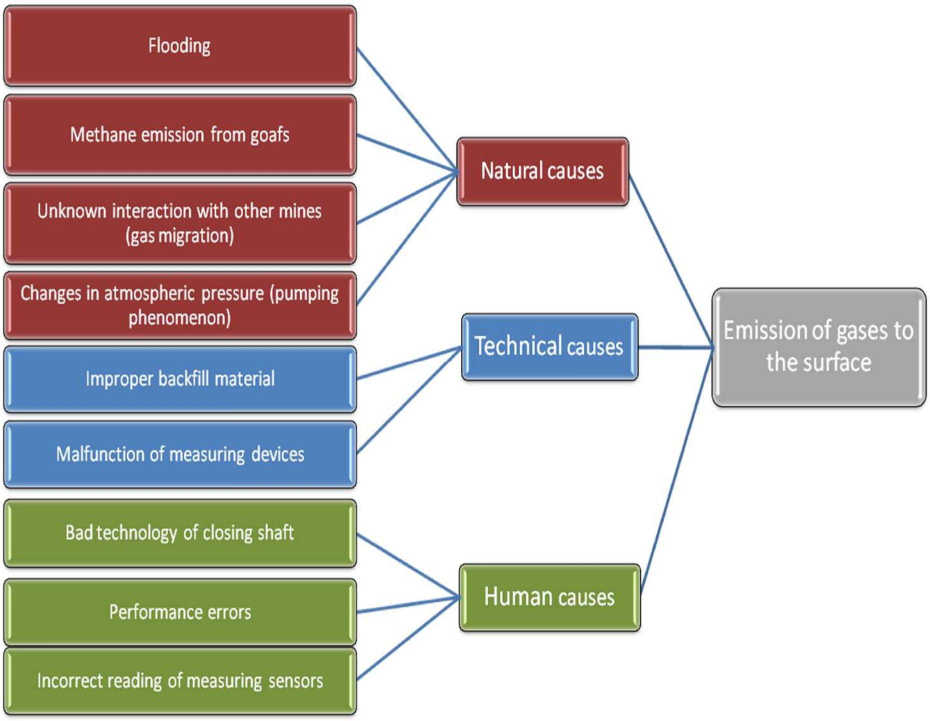
Assuming that switching off the fans is the initial point, the process of closure can be divided into four stages.



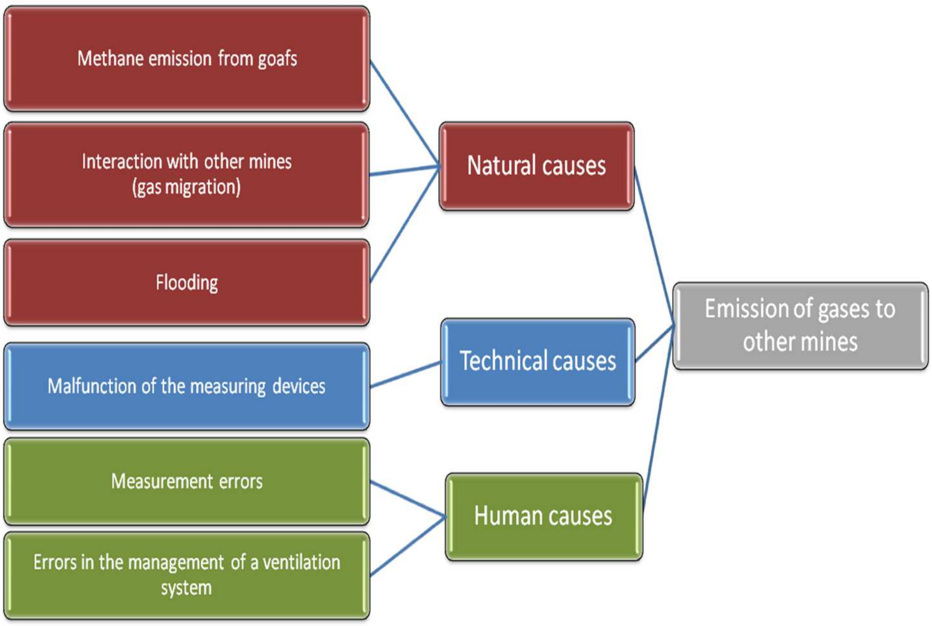
Stage 1: Period of closing shafts

This stage represents the period of closing shafts

Division of factors influencing risk associated with the emission of gases to the surface.



Division of factors influencing risk associated with the emission of gases to another mine.

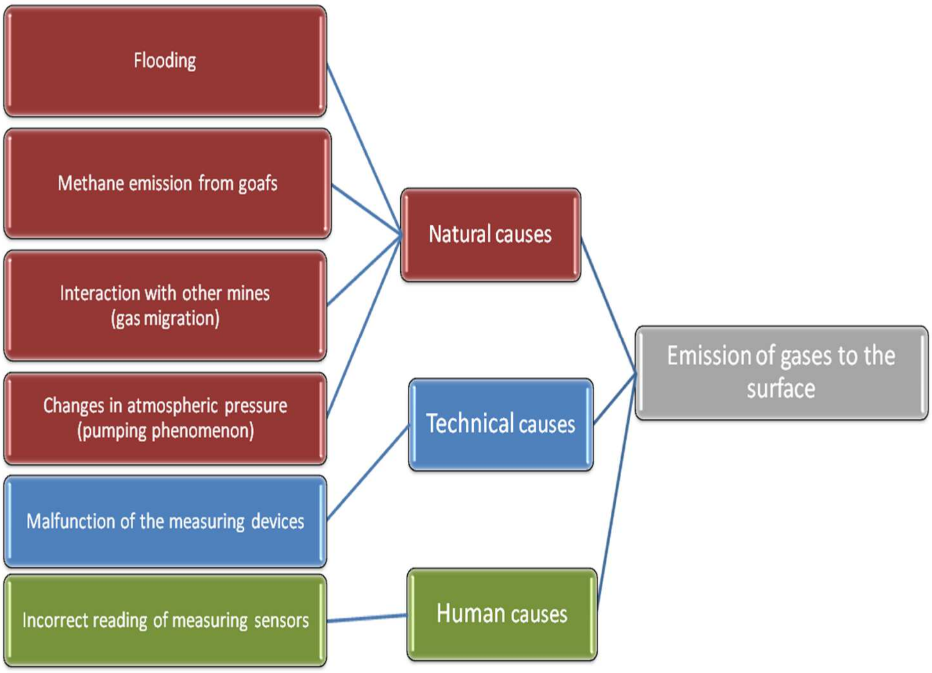


Stages 2 and 3: Period of stabilizing the volume of voids

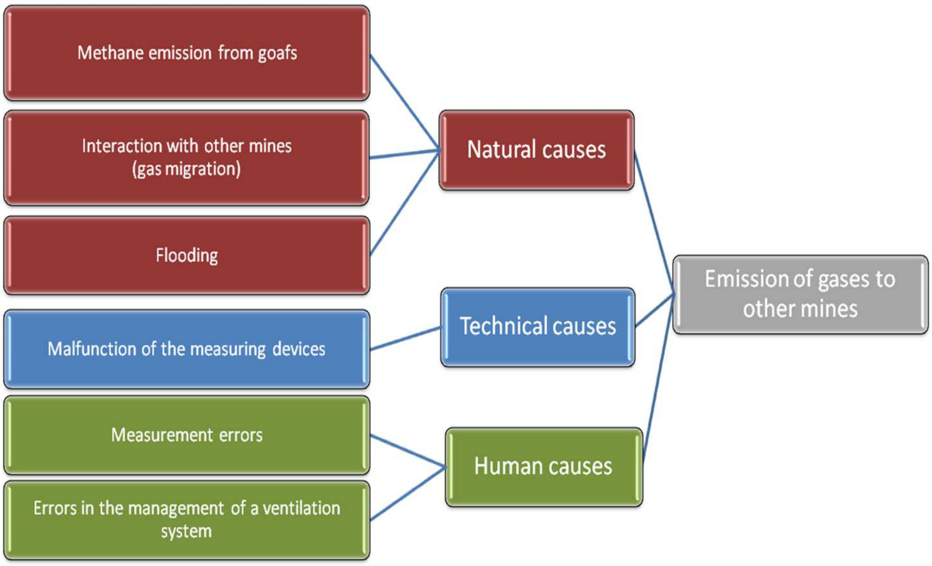
Due to the parallel course of the process of flooding mine workings and gas emission, Stages 2 and 3 are analysed together.

These stages represent the periods of stabilizing the volume of voids and when the closed mine is treated as a reservoir. Also during these stages, the process of flooding mine workings continues till the end.

Division of factors influencing the risk associated with the emission of gases to the surface.



Division of factors influencing risk associated with the emission of gases to another mine.



Stage 4: Period of possible changes caused by external factors

This stage represents the period of possible changes caused by external factors, the influence of another mine on the closed mine, the conducting of activities associated with producing methane from the closed mine, and when the emission of methane from goafs is finished.

During this stage new conditions and circumstances, which cannot be forecasted, e.g.: plans of closing another mine connected with the already closed one.

New circumstances may trigger new factors, yet, first of all, they will result in an increase in the risk associated with already identified factors, e.g. flooding another mine may result in an increase in the level of water in a mine which was already closed.

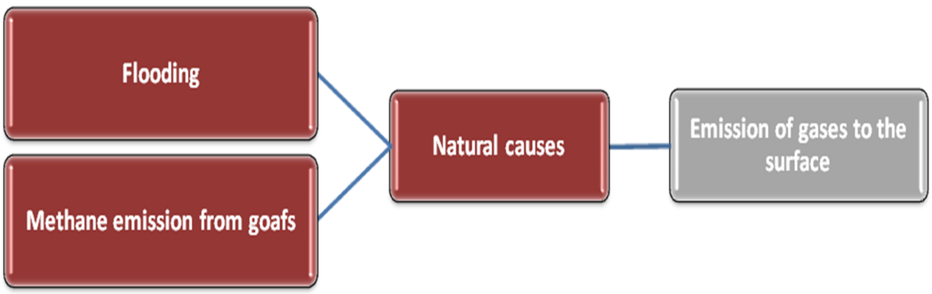
Similarly, migration of larger volume of gases between mines may occur, depending on the difference in pressure.

Thus, the diagram for the Stage 4 will be the same as during Stages 2 and 3, supplemented with new factors when they will occur.

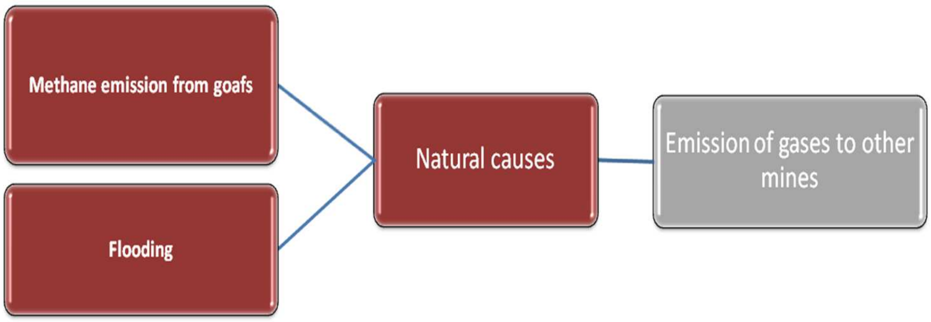
Reduced diagrams

Reduced diagrams containing only the elements for further analysis are presented below.

Reduced diagram of the division of factors influencing the risk associated with emission to the surface (Stage 1).



Reduced diagram of the division of factors influencing risk associated with the emission of gases to another mine (Stage 2 and 3)



Risk assessment: Risk identification (radon)

The most important factors influencing radon concentration in a rock body are the contents of uranium and radium in the mined layers and in the overburden.

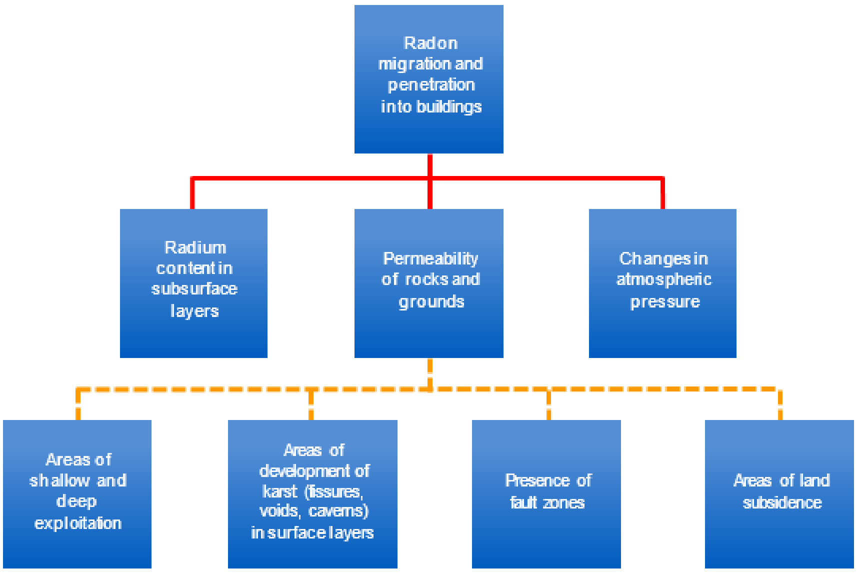
The process of radon transport is controlled by the permeability of the ground, thus any cavity that exists under the overburden has the potential to accumulate elevated radon concentrations. Another group of factors producing changes in the physical properties of rocks, which enable radon migration, are mining-induced effects such as the formation of voids, depressions, and subsidence of the surface, or rejuvenation of fault zones. The numerous cracks and fissures associated with faults constitute preferential pathways for gas migration. Changes in the concentration of radon in the air entrapped in the soil allow the path of faults to be tracked.

The mining practice confirms that mining exploitation rejuvenates fault zones, which are the source of mining tremors. The stress state of the rock mass, altered because of mining exploitation, can cause the loosening and disintegration of rocks. This is the reason for the release and migration not only of methane but probably also of radon. According to the literature, the local zone of rock weakening along the fault in some cases it can reach up to several meters on both sides.

Due to rock disintegration, the surface and volume from which radon exhales, and migrates can be significant. Moreover, the transport of gases through a newly created pathway to the surface is easier than through an undisturbed structure.

German scientists had observed that significantly higher concentrations of radon in the soil are measured in a relatively narrow zone, the boundary of which overlaps with that of the area of subsidence of the surface above the exploitation area.

The diagram below presents the dependence in form of branches of the fault tree with logic gates: “OR” (orange dashed line) and “AND” (red solid lines).



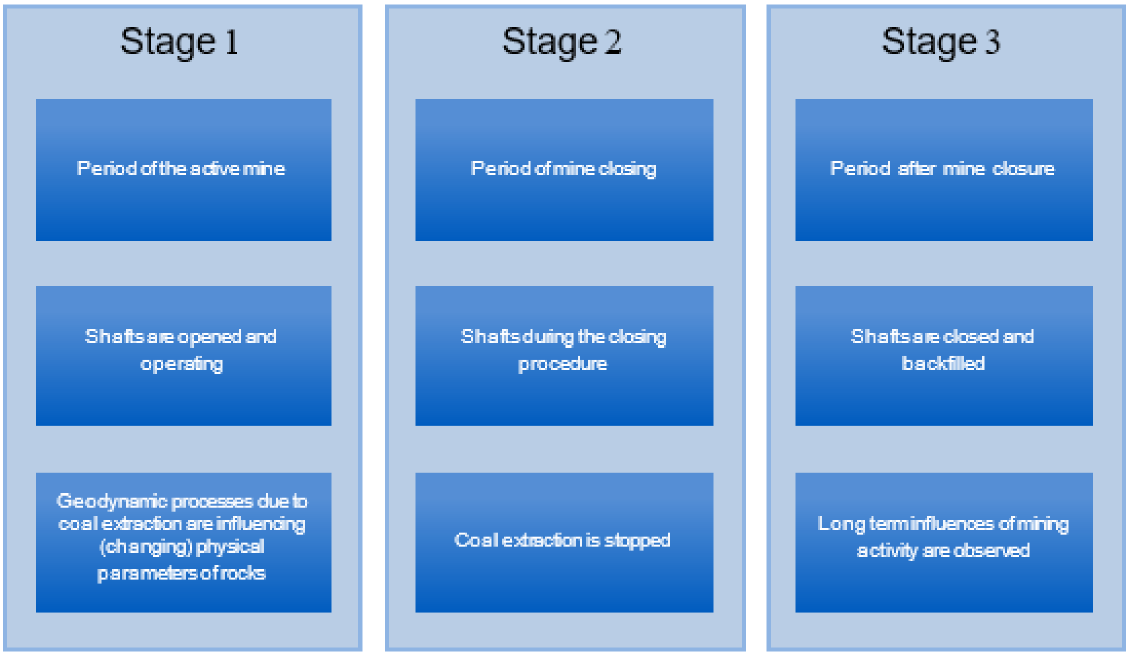
The areas where radon emission to the surface and its penetration into buildings can occur are: the sites where mining operations were conducted close to the surface, the areas affected by faults, areas of settlement and the areas of closed shafts.

It is generally considered that the sites of the disintegration of the surface layers, due to the above factors 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.

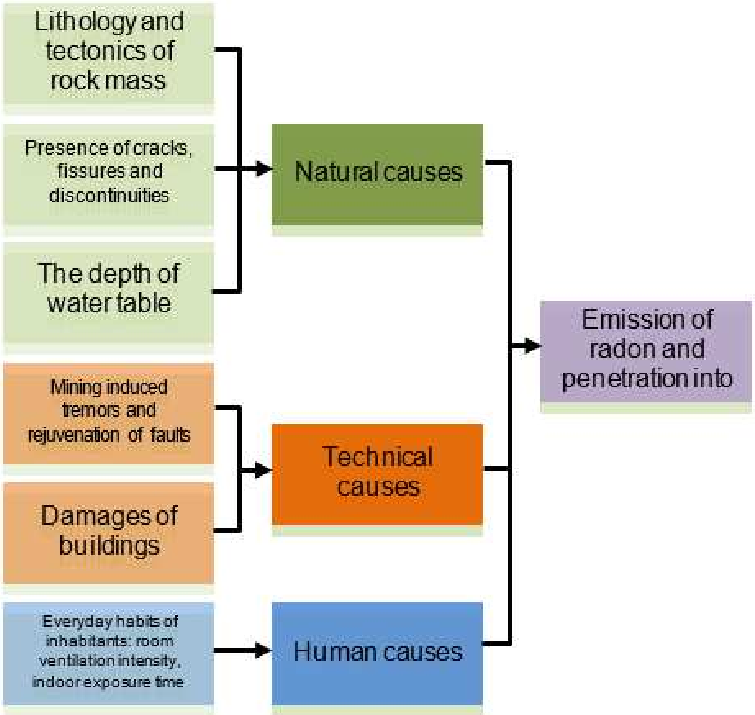
The phenomenon of radon migration and penetration into building in mining and post-mining areas could be presented in three stages:



Stage 1: Period before the mine closes

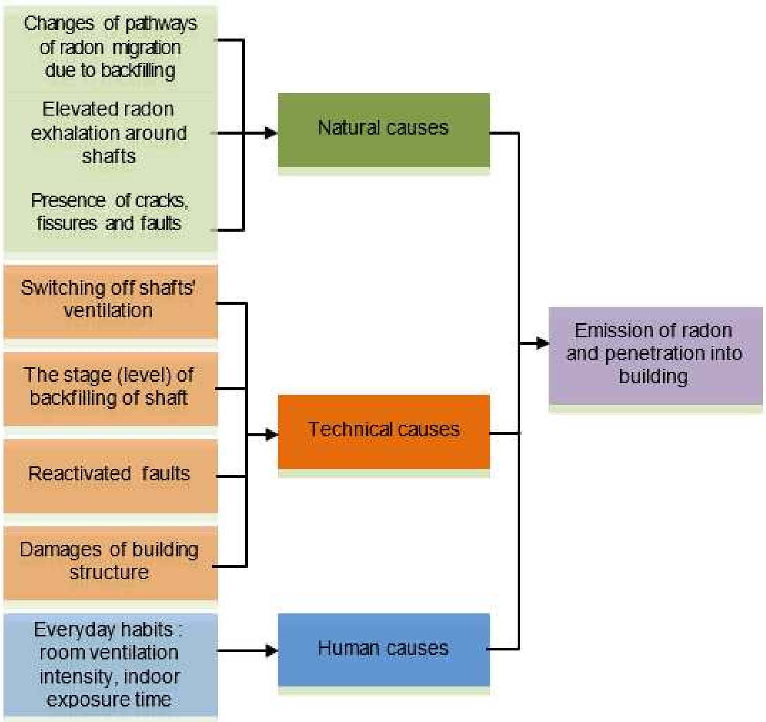
This stage represents the period before the mine closes. Shafts are opened and operating. Geodynamic processes due to coal extraction are influencing (changing) physical parameters of rocks.

Description of factors influencing risk associated with the emission of radon gas to the surface are presented below.



Stage 2: Period of mine closing

Period of mine closing. Shafts are under the procedure of closing. Coal extraction is stopped. The presentation of factors influencing the risk associated with the emission of radon gas to the surface and penetration into buildings is shown below.

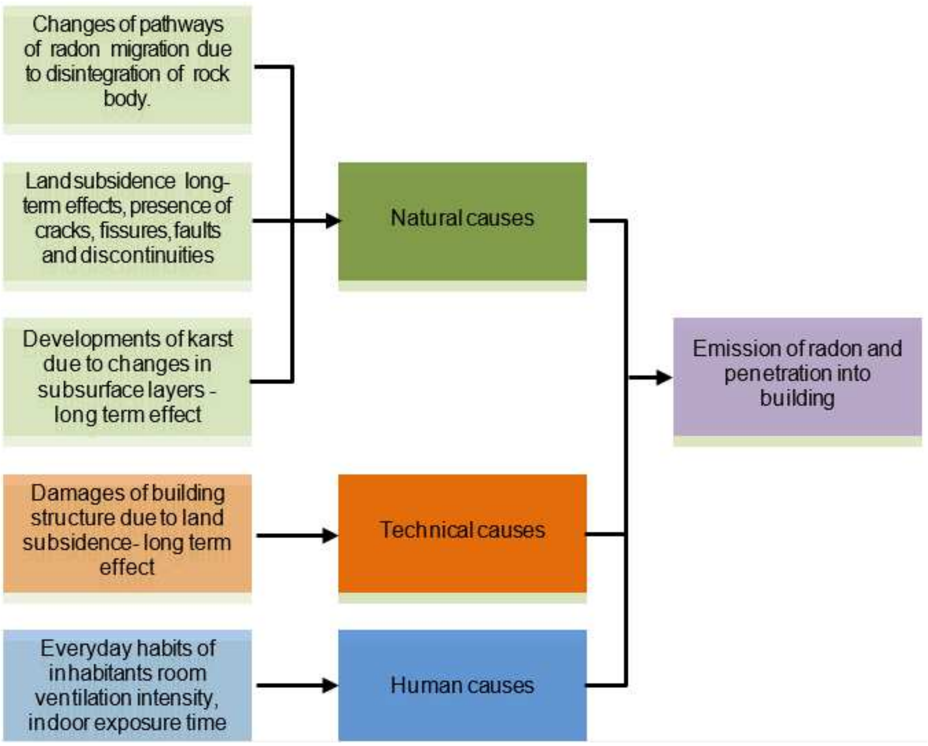


Stage 3: Period of mining termination

This stage represents the period of the mining termination and finalization of the all procedures connected with mine closure. Possible changes of radon migration are caused by long term phenomena such as the disintegration of subsurface layers due to land subsidence. It was found that total land subsidence in specific post-mining areas reached up to 20 m, causing linear discontinuous deformations of the surface in the form of fractures and fissures. Other long term effects enabling radon migration are changes in the depth of the groundwater layer, dewatering of rock body.

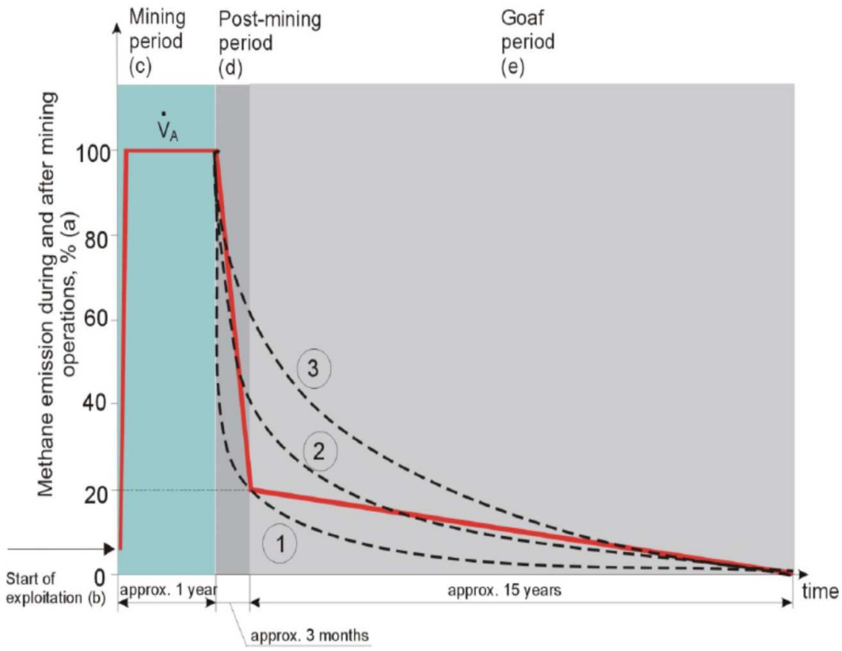
During this stage (lasting even several years after the closure of the mine) there may occur sudden land collapse, creating funnels and sinkholes or development of karst phenomena.

The presentation of factors influencing the risk associated with the emission of radon gas to the surface and penetration into buildings is shown below.



Risk assessment: 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.



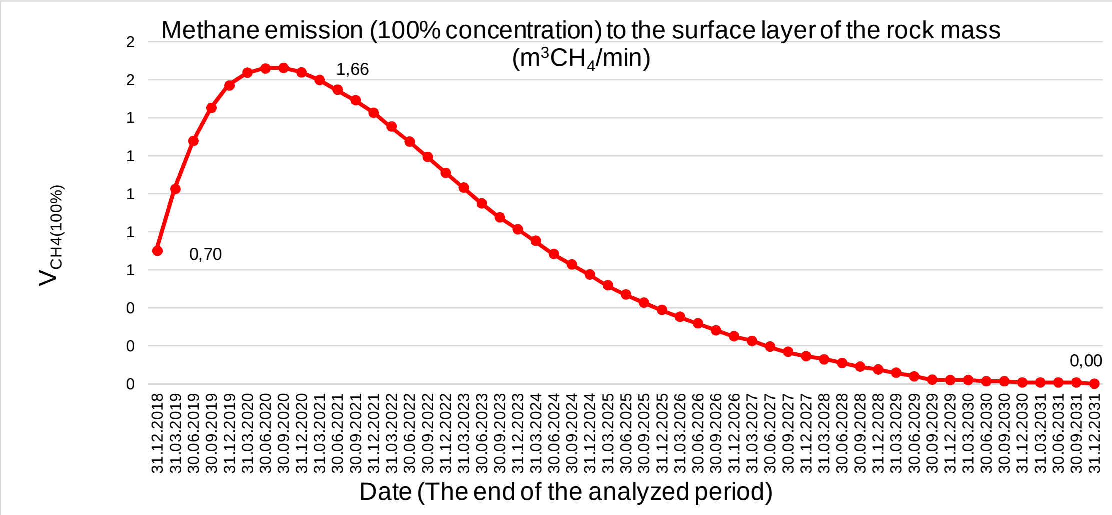
To assess the risk associated with methane emission, the amount of the gas emitted from the goafs was analysed. The analysis concerned a period of 15 years after the mining operations in the last longwall stopped .

The analysis included all the longwalls in Anna mine, also the influence of partial flooding of the goafs was considered. The analysed longwalls together with information on the percentage of flooding are presented in the table below.

Seam	Longwall	Year of flooding	Flooded part [%]
703/1-2	R-15	2018	0.35
703/1-2	R-14	2018	0.68
707/1-2	G-5	2018	0.06
707/1-2	R-14	2018	0.7
707/1-2	R-15	2018	0.65
713/1-2	G-1	2018	0.11
713/1-2	R-16	2018	100
713/1-2	R-15	2018	0.96
713/1-2	R15a	2018	0.87
718/1-2	J-2	2018	0.19
718/1-2	J-3	2018	0.91

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.

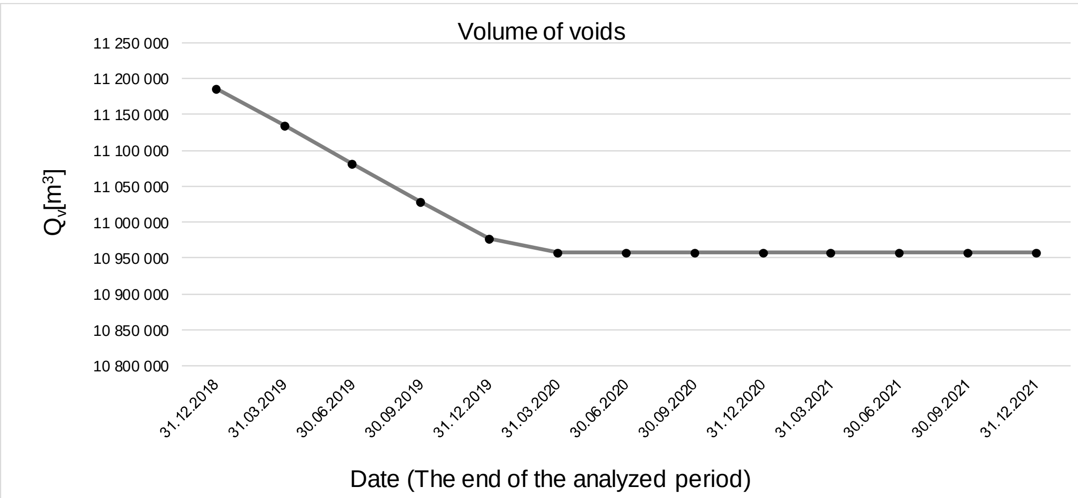
The course of methane emission in the analysed period is presented in the graph.



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.

The course of changes in the volume of voids is presented in the graph below.



According to the calculations, by the end of 2020, the inflow of water ought to stabilize.

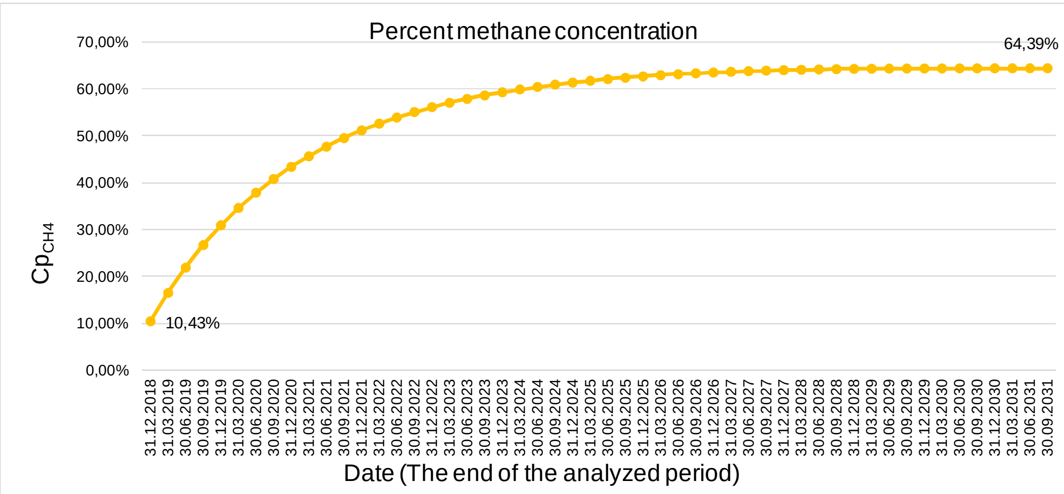
The water flowing into the closed mine workings will overflow into the mine workings of Rydułtowy mine, and then it will be pumped, thus, in the following years there will not be any changes in the volume of voids in the closed mine.

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 MERIDA project.

The concentration of methane in mine workings will change proportionally to the amount of inflowing methane. At the beginning of Stage 2 it will be 10.43% CH_4, and at the end of Stage 3,64.39% CH_4.

The course of changes in methane concentration resulting from the emission of methane from goafs and flooding mine workings during the closure of Anna mine are presented below.



According to conducted analysis the greatest increase in methane concentration will occur between 2020 and 2022.

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.

Hence, during initial risk evaluation the simulations with VentGraph-Plus software were also conducted.

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. The simulations were conducted for stages of mine.

Radon

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, 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).

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.

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.

In most countries the uniform method for assessing the risk of radon penetrating from the underlying soil or bedrock, based on determining the radon index of the building site, proposed by Czech scientists, is implemented – see table below.

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

Within the frame of MERIDA project both groups of measurements required (recommended) for risk evaluation were performed. The obtained results are the basis for the risk evaluation.

Risk category	Radon concentration in soil, C_{Rn} (kBq/m^3)		
Low	$C_{Rn} < 30$	$C_{Rn} < 20$	$C_{Rn} < 10$
Medium	$30 \leq C_{Rn} < 100$	$30 \leq C_{Rn} < 70$	$10 \leq C_{Rn} < 30$
High	$C_{Rn} \geq 100$	$C_{Rn} \geq 70$	$C_{Rn} \geq 30$
	Low permeability	Medium permeability	High permeability

Source: 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.

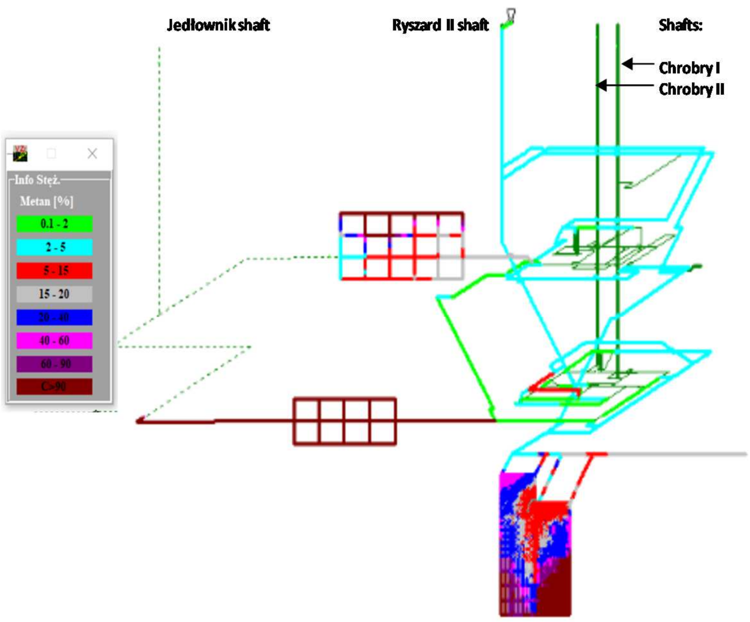
Risk assessment: Risk evaluation (methane)

Stage 1: Period of closing shafts

The stage concerns the period when the process of the ventilation closure of a mine is not finished yet. For Anna mine, it was the stage of closing shafts. When the ventilation system of Anna mine was separated from Rydułtowy mine, Ryszard II and Chrobry I shafts were being closed.

To verify the places of gas migration to the surface, "reservoirs" where methane from goafs gets collected were modelled. Basing on the aforementioned modeling and the VentGraph-Plus simulation, the places of migration of gases from Anna mine were determined.

Distribution of methane concentration in ventilation network and goafs after the fan stoppage and during filling the shafts (July 2018) is shown below.



As the above diagram shows, the place of migration of gases is Ryszard II shaft which is being closed. Hence, the personnel involved in closing the shaft and people in its vicinity will be exposed to the highest risk associated with the migration of gases.

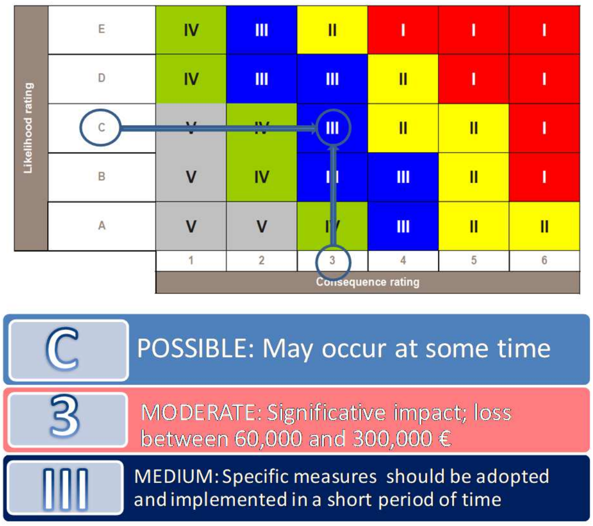
The nearest buildings are located approx. 80 meters away from Ryszard II shaft. These are detached houses. The rest of the area is covered with vegetation mainly in form of meadows and trees.

According to the conducted analysis, the consequences of gas emission will refer mainly to methane. The VentGraph-Plus simulation shows that the concentration of methane in the shaft ought not to exceed explosion concentration (5%).

However, bearing in mind that there are possible local concentrations of methane and that it may migrate in the shaft at the explosion concentration, it is impossible to assume that there is no risk of an explosion. Such events occurred in the past, both in Poland (during the closure of shaft no. III in Morcinek mine) and in the Czech Republic (the closure of shaft He-III in Odra mine). Probability of such an event was assumed to be medium as similar events occurred in the past.

The consequence of an explosion would be destruction of the infrastructure for backfilling the shaft: ramps, vehicles, conveyors and injuries to the personnel conducting the closure works (accidents). The explosion could also result in the damage to the residential buildings located within approx. 80-120 meters from the place where the works are conducted.

The results obtained by applying the proposed methodology of risk assessment are presented below.

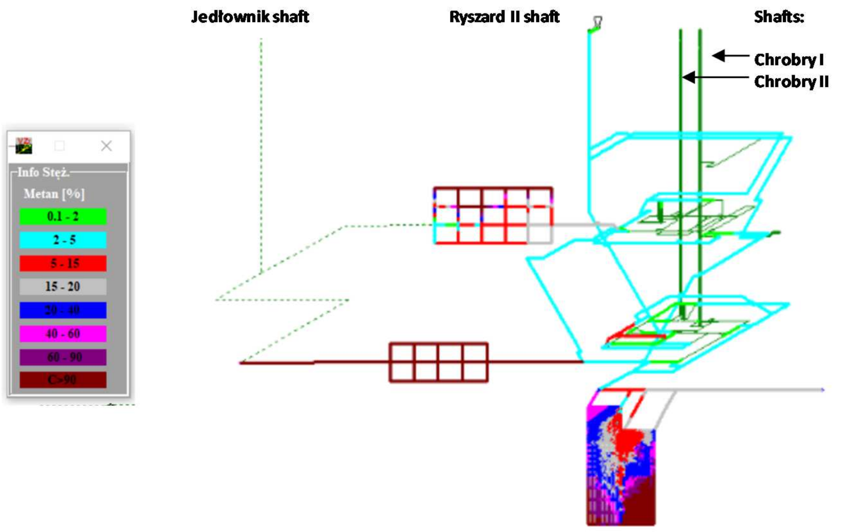


Stages 2 and 3: Period of stabilizing the volume of voids (with the assumption that Rydułtowy Mine ventilation system is operating)

The stages consider the period when the shafts are completely closed and in the voids of the closed mine the volume and the concentration of methane increase; and with the assumption that Rydułtowy Mine ventilation system is operating

As the process of closing shafts continues there is no risk associated with an explosion in a shaft. However, there is risk associated with methane migration into wells and basements of detached houses and public buildings. The consequences will depend on the identified places of possible migration of gases. For the Ryszard II shaft area, they will be lower, as there are no consequences like destruction of machinery and accidents of the personnel involved during the shaft closure.

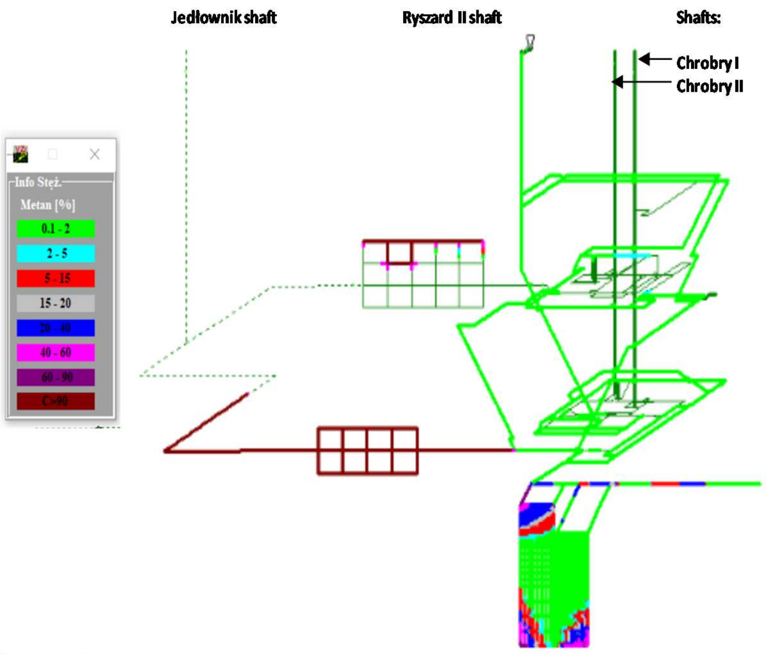
The results of VentGraph-Plus simulation indicating methane concentrating in mine workings leading to Jedłownik shaft, in November 2018, deserve special attention. Distribution of methane concentration in former ventilation network and goafs after securing the shafts with concrete caps and sealing the connection with Rydułtowy mine is presented below.



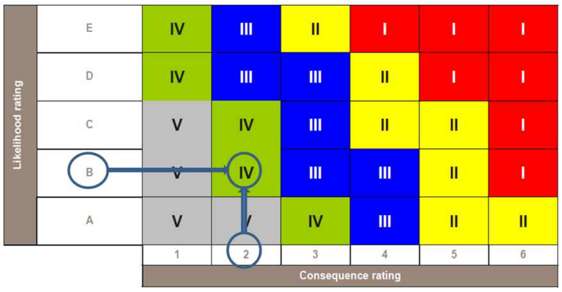
The closest building in the vicinity of Jedłownik II shaft are located approx. 50 meters from the shaft. They are a housing estate with blocks and public buildings. The concentrations of methane will not reach the area of Jedłownik shaft within the period when methane is emitted i.e. until July 2033.

Over the places where methane concentrates there are layers which make its migration to the surface layers impossible. Hence the risk associated with migration of the gas to the surface is low despite an increase in the amount and concentration of methane in voids of a closed mine.

Distribution of methane concentration in former ventilation network and goafs after securing the shafts with concrete caps and sealing the connection with Rydułtowy mine (July 2033) is presented below.



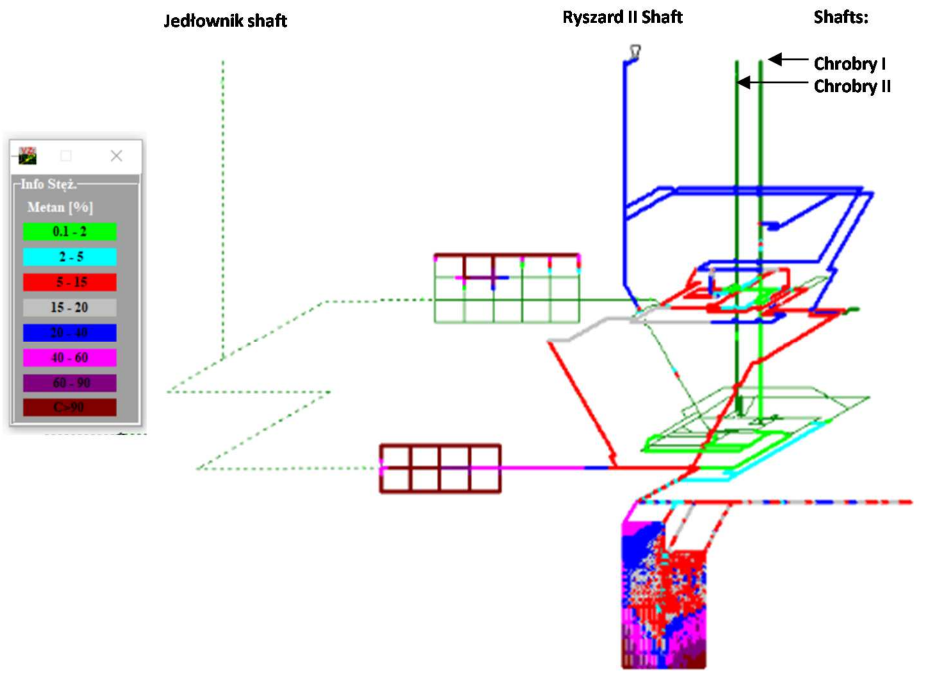
Following the above, there is no need to introduce additional solutions to minimise the risk.



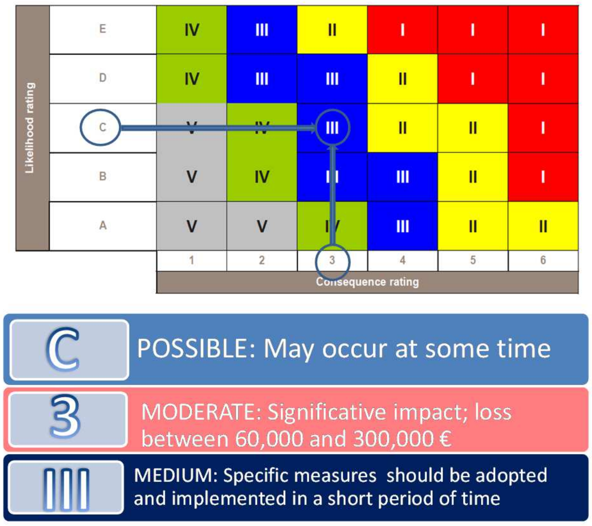
B	UNLIKELY: Not likely to occur in normal circumstances
2	MINOR: Very low impact; loss between 10,000 € and 60,000 €
IV	LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.

Stages 2 and 3: Period of stabilizing the volume of voids (with the assumption that Rydułtowy Mine ventilation system is not operating)

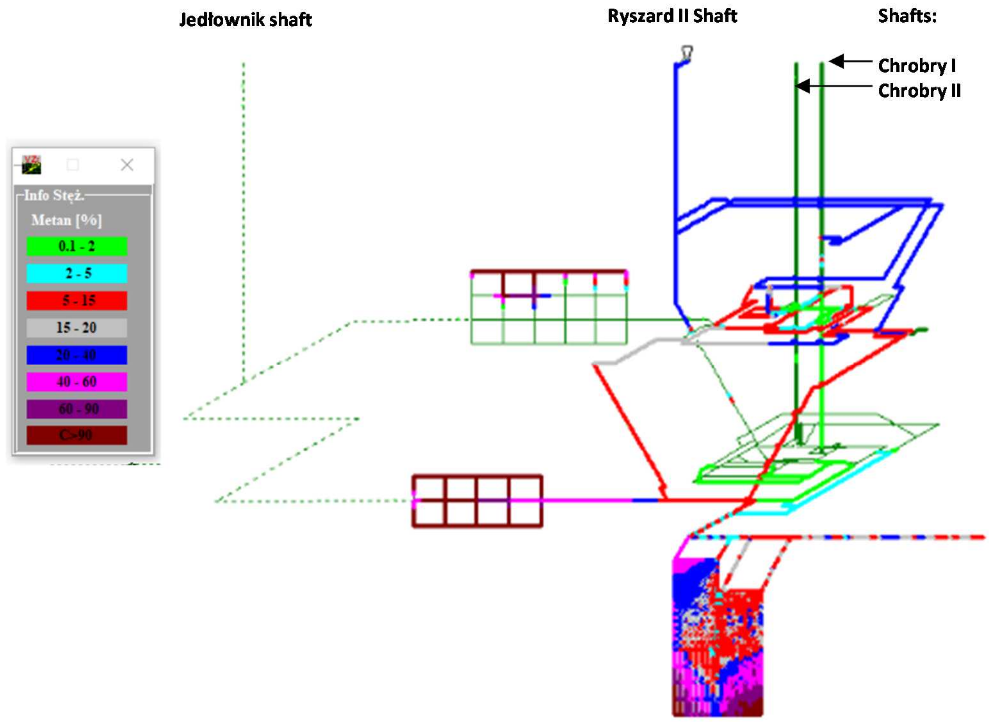
Such an assumption is justified considering the deposits in Rydułtowy coal mine and its closure planned in 2030. When the fans in Rydułtowy coal mine are turned off as a result of the closure process the risk of gas migration will change as follows.



The presented results of simulations show possible significant concentrations of methane in the area of Ryszard II shaft. Taking it into consideration together with the fact that the shaft is closed, the explosion risk in the shaft area was evaluated to be medium.

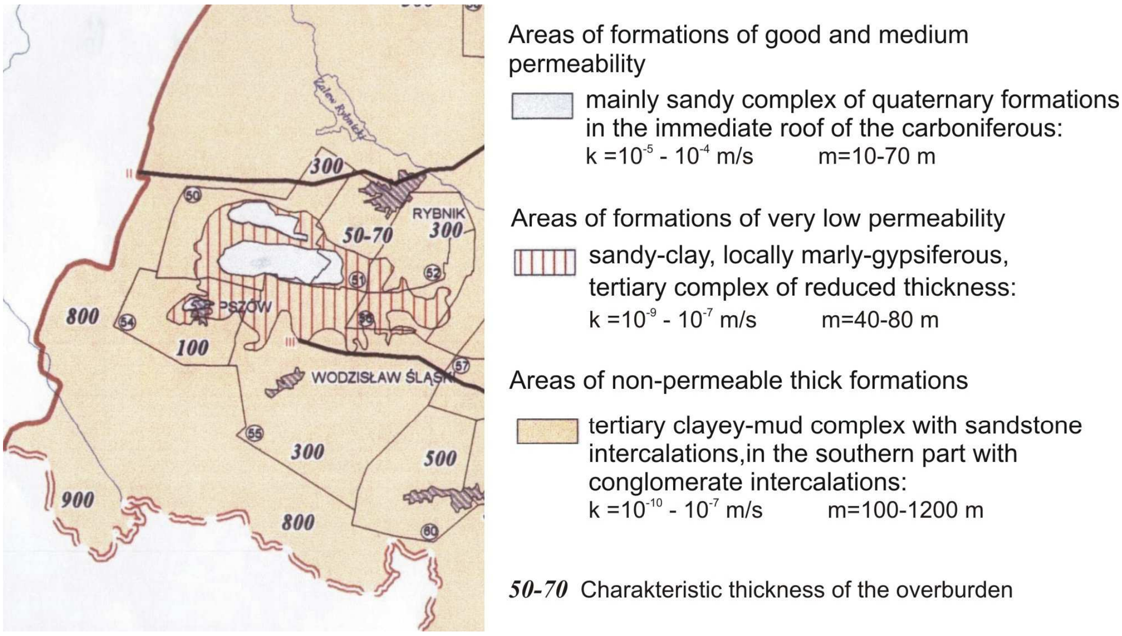


As the figure below shows methane concentration in Jedłownicki drift connecting Jedłownik shaft with the mine workings of Anna coal mine, possible gas migration to the near-surface layers was analysed.



In the area of the drift here are numerous faults which may be a route for gas migration.

Due to the presence of faults in the area permeability of Carboniferous overburden located above the faults was analysed. The analysis showed that in the area there are present only virtually impermeable and low-permeable geological formations(impermeable and low-permeable layers).



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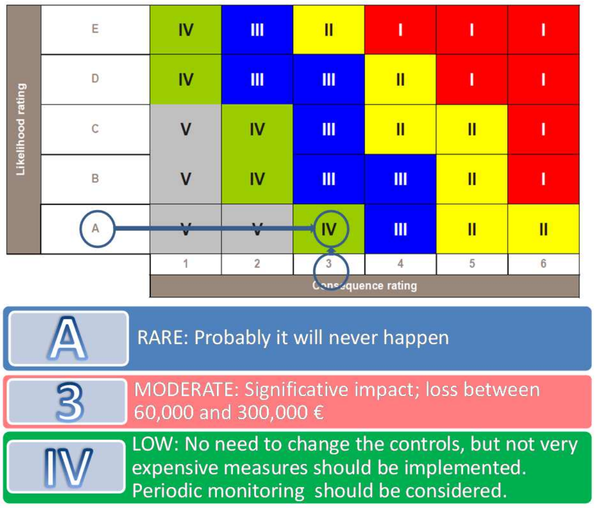
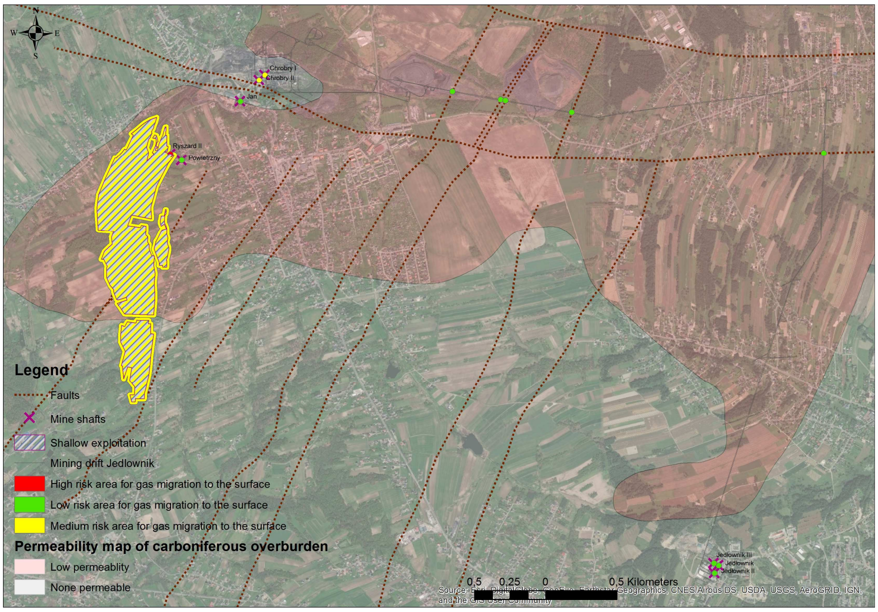
The gas risk in the area of the Jedłownicki drift was determined to be low.



As 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 very low for Stages 2 and 3 lowering the risk level will concern only the areas of shallow exploitation and shafts marked in red and yellow.



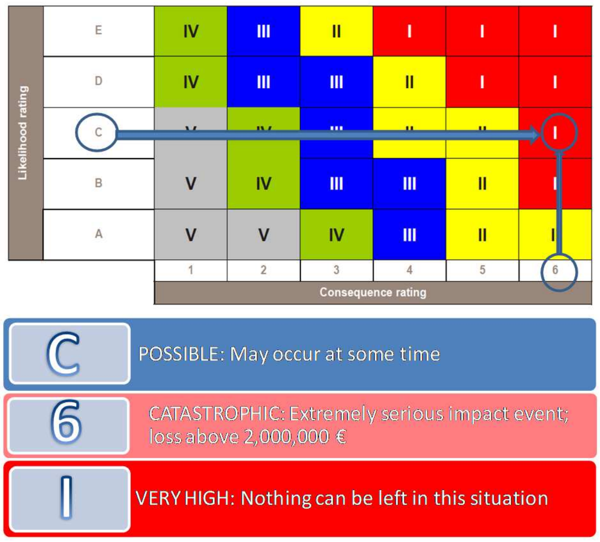
Emission of gases to another mine

Excavations of the Anna mine are adjacent to the excavations of the active mine Rydułtowy. There has been no ventilation connection since the period of liquidation of the shafts between the mines.

However, there is still a risk of gas migration to the Rydułtowy mine due to the discontinuities of the rock mass and under pressure produced by the ventilation system of the Rydułtowy mine.

Migration of gases to the Rydułtowy Mine will increase the risk associated with the methane explosion. The consequences of an explosion depend on its place and strength.

The result of an explosion may be the death of employees, the destruction of machinery and equipment, and even the inability to continue to operate in the destroyed part of the mine.



Risk assessment: Risk evaluation (radon)

Stage 1: Period before the mine closes

The stage concerns the period when the mine is still operating. In the area 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 (Rydułtowy-Anna colliery) as in entire Upper Silesia, coal mining generates considerable changes in rock mass such as surface subsidence and tectonic discontinuities along fault zones generated by mining-induced geodynamic phenomena (underground tremors and bumps).

Another phenomenon that might occur is the development of zones of karst process 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.

Similar phenomena occur in the surroundings of shafts, especially the old ones, which have not been operating for many years. Results of radon measurement in soil gas showed that in some places the values exceeded the limits used for radon risk evaluation eg. 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* town was estimated.

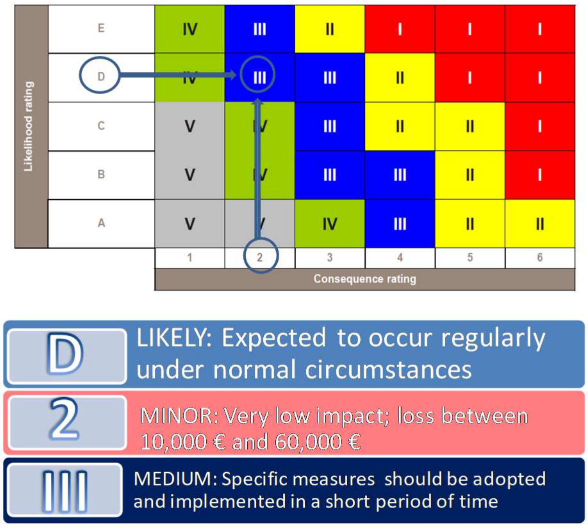
Additionally, we assessed the number of smokers, because risks associated with smoking and exposure to radon are synergic.

According to our calculations, the total annual number of cancer cases and probable fatalities is 3.6. and related to the number of inhabitants of Rydułtowy Community and statistical number of smokers in the area.

According to WHO (WHO Handbook on indoor radon, 2009) and the report on Lung cancer in Poland (2016), the cost of medical treatment for 1 person in Poland is about 14,000 €.

Therefore, the estimated total costs due to exposure to radon would be about 56,000 €.

The results obtained by applying the proposed methodology of risk assessment are presented below.

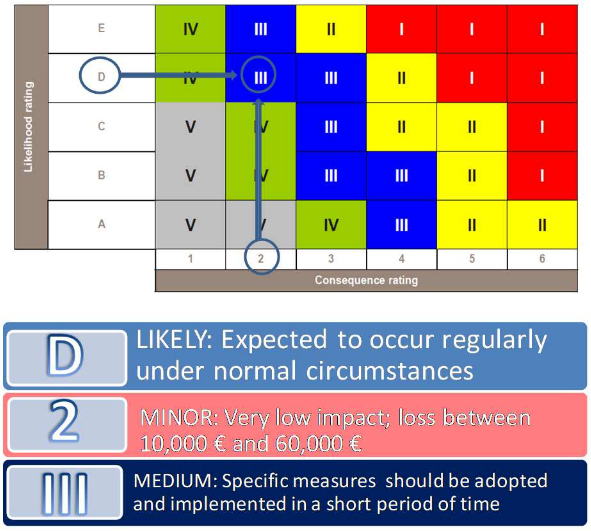


Stage 2: Period of mine closing

The stage considers the period when the shafts are during the closing procedure. The pathways of radon migration are changed due to shafts backfilling. It may occur that in the areas in the vicinity of closed shafts radon emission increases and radon penetration can be expected.

The mentioned above factors may cause an increase in radon risk. Countermeasures to be taken are: sealing of the damages in the building structure, less often - installing pumps to reduce radon concentration.

Measurements showed elevated radon concentration in soil gas in the area of Ignacy and Powietrzny 3 shafts. 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. It was assumed that the number of inhabitants of *Rydułtowy* town who probably will die annually because of lung cancer caused by increased concentration of radon and its short-lived progeny is the same as in the case of Stage 1. Therefore, the total cost of risk due to exposure to radon is about 56,000 €.



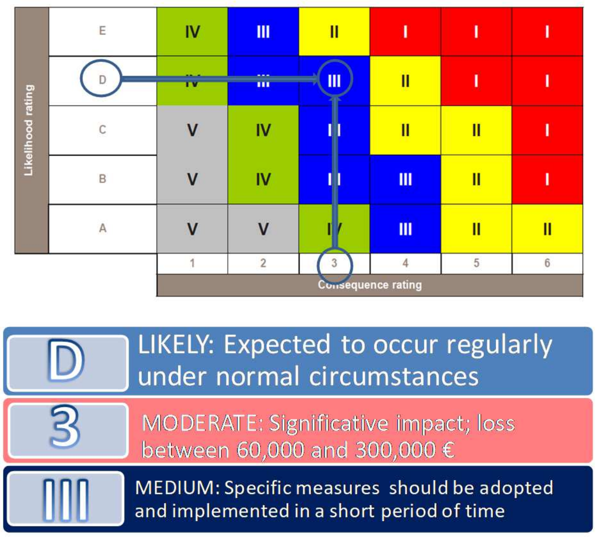
Stage 3: Period of mining termination

The stage considers the period when the shafts are closed. In the area of past mining activity, the important factor influencing the migratory ability of radon is the mining-induced transformations taking place in a rock mass, such as surface subsidence and tectonic discontinuities along fault zones generated by mining-induced geodynamic phenomena. The underground tremors and bumps may still occur for some time after the coal mining operation has stopped. This process causes enhanced permeability in fault zones and may lead to increased levels of radon in soil gas. Another phenomenon observed in specific sites of post-mining areas is the development of zones of karst process causing the disintegration of rock body, which eventually enables the migration of radon.

The mining-induced dislocations and damages have a strong influence on the foundations of the building, creating cracks in floors and walls (see picture). The area in which long-term changes in the rock mass in the post-mining area can be significant. The boundaries of the basins of subsidence above the cavities caused by coal extraction significantly exceed the range of underground goafs.

Measurements showed elevated radon concentration in soil gas in the area of Ignacy shaft. The measured value of radon in soil gas concentration – above 40,000 Bq/m^3 - suggests a classification of the building site as a medium risk area.

We assume that subsidence and destruction of buildings are still progressing for some time (maybe decades), after the mine has been closed. Probably elevated radon concentration will be measured in a larger number of buildings than in previous stages. We suppose that the concentration of indoor radon during the period of Stage 3 may increase by 100 Bq/m^3. In such a case the total number of people that probably would die annually because of lung cancer due to exposure to radon, is estimated at 4.64 (smokers and non-smokers), and estimated costs of medical treatment would be about 65,000 €.



Risk assessment: Proposed treatments (methane)

Stage 1: Period of closing shafts

To minimise the existing risk, it is necessary to take steps to monitor constantly methane concentration in the shaft during its closure.

A gasometer system operating at the Rydułtowy Mine was used for measuring the methane concentrations. The sensor was located below the remains of the ventilation duct. A cyclic measurement was performed. The warning threshold has been set to 0.75%. In case of exceeding the warning threshold, an alarm was triggered - sound and light signalling in the mine dispatcher's room.

Stages 2 and 3: Period of stabilizing the volume of voids

Due to the possibility of significant concentrations of methane in the Ryszard shaft, it is possible to apply AMM (abandoned mine methane) technology. AMM technology is significantly reducing the risk of uncontrolled emissions at the surface, exploiting an otherwise wasted gas resource and mitigating GHG emissions. This approach is in accordance with the guidelines of United Nations Economic Commission for Europe as published in Best Practice Guidance for Effective Methane Recovery and Use from Abandoned Coal Mines.

Depending on the results of measured methane concentrations in the shaft and gas pressure, flares, gas vents, or gas engine may be used. Costs for a flare is estimated to be 3,000 € based on different experiences. To minimise the explosion risk for the area of Ryszard II shaft it is necessary to prohibit construction of buildings within 20 meters of the closed shaft.

In the area of shallow exploitation, it is necessary to demarcate a zone expanded by 20 meters 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. Thus, the cost can be easily afforded by the owners of buildings located in the risk area. There are 25 buildings in the risk area where gas leak detectors should be installed. An MTG-3000H Gas Leak Alarm may be applied.

The residents shall be informed about the need to apply the detectors and it shall be verified by the inspectors checking the ventilation systems in the buildings located in the danger zones.

Emission of gases to another mine

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 center. 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. In the Rydułtowy mine, sensors such as CSM-3, CMN-5, MM-2, MM-2PW, MM-4, CSM-1 are used for the gasometer system.

Risk assessment: Proposed treatments (radon)

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, see an example of the system offered by RADOVENT Company below.

During Stages 1 and 2 the proposed sufficient methods of reduction of radon gas concentration in buildings should be:

- 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;
- 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.

During Stage 3, it was assumed that average radon concentration in a certain number of dwellings might increase by 100 Bq/m^3.

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.

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.

In other buildings, basic preventive measures such as intensive ventilation by opening windows should be sufficient.

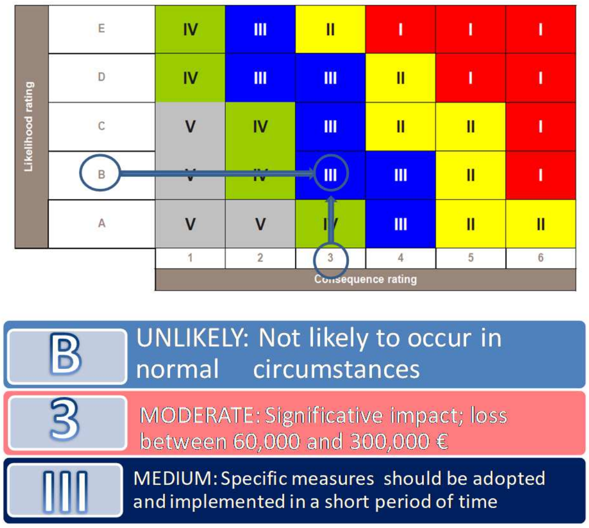
Risk assessment: Performance forecast (methane)

Stage 1: Period of closing shafts

The monitoring will lower probability of an explosion. It is difficult to limit consequences of the event as it is difficult to eliminate the machines and equipment used to conduct the works and it is impossible to move the buildings located in the shaft area.

The only viable way to limit the consequences is limiting the number of personnel during the works.

The introduced solution aimed at minimizing the risk, will lower probability of an explosion, yet it will not change level of risk.

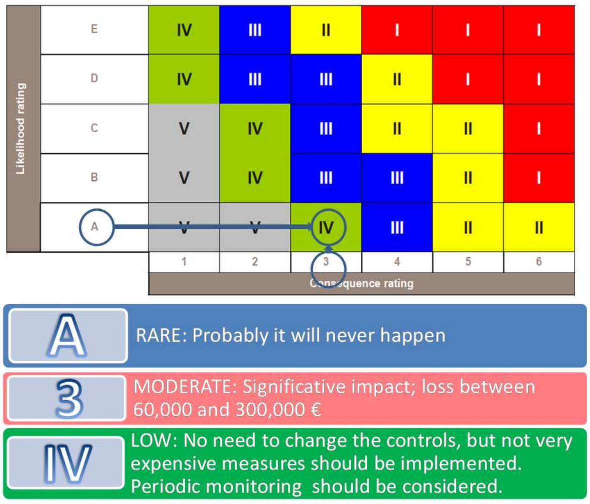


Before publishing this document all the works within Stages 1 and 2 were completed. We have learned that during that period there was no explosion of methane and no concentrations of methane were observed during the measurements in the shaft area.

Stages 2 and 3: Period of stabilizing the volume of voids

By applying AMM technology and monitoring gas concentration in the buildings located in the area of shallow exploitation and prohibiting construction of buildings within 20metres of the shaft, the likelihood of a gas explosion will be significantly reduced.

Lowering the likelihood of a gas explosion also resulted in gas risk going down to be low.

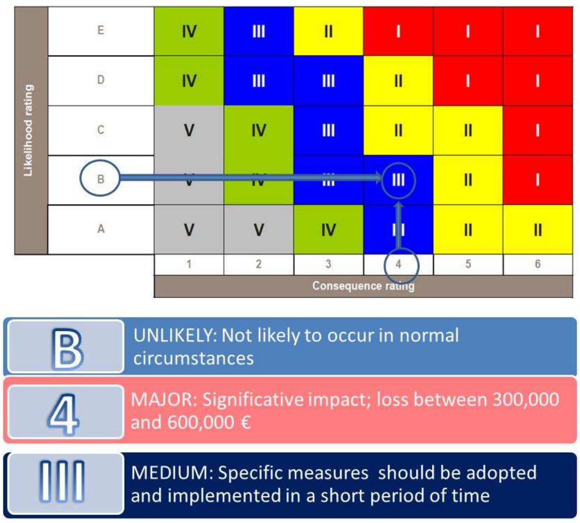


Emission of gases to another mine

The monitoring will lower probability of an explosion.

Identification of places where methane inflows from the closed mine to the active mine will allow for the use of additional anti-explosive barriers in these areas. This solution will prevent the spread of the explosion to the areas of the mine where the miners work and the expensive equipment is located. Thus, the ranking of consequences will be significantly reduced.

The introduced solutions aimed at minimizing the risk will lower level of risk.

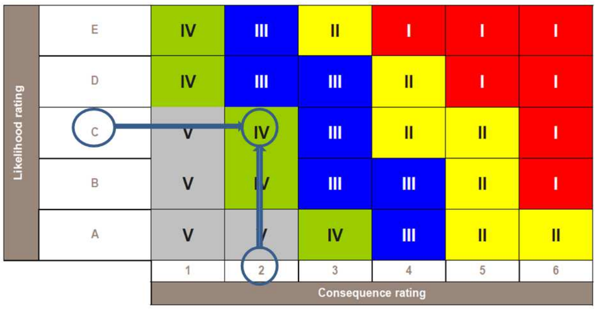


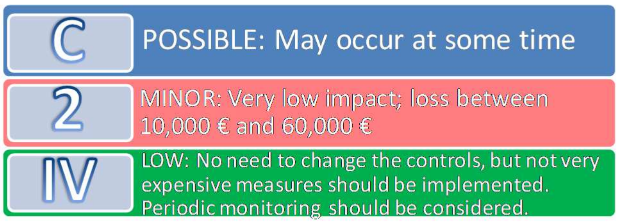
Until December 2019, the Rydułtowy mine gas system did not register any increased methane concentrations that could be a result of gas migration from the Anna mine.

Risk assessment: Performance forecast (radon)

The introduced actions for all stages will reduce the concentration of radon. The lung cancer medical treatment costs would be reduced by 9,000 €, assuming that the membrane would be placed over exposed soil and as the result radon concentration is reduced by 50%.

Through these actions, the likelihood of the inhabitants of this area getting sick and hence the cost of their medical treatment will be lowered. Through these actions, the risk associated with the emission of radon to the surface decreases to the lower level.





Economic evaluation: Cost evaluation

We will only consider gas risk (including radon) after the close of the mine.

To minimise the explosion risk for the area of Ryszard II shaft it is necessary to prohibit construction of buildings within 20 meters of the closed shaft. In the area of shallow exploitation, it is necessary to demarcate a zone expanded by 20 meters 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. There are 25 buildings in the risk area where gas leak detectors should be installed.

With an estimation of a 100 € including installation and a total of 400 building or small houses maximum that can be affected, the cost of the detectors will be:

Cost of detectors = 100 € x 25 = 2,500 €

The yearly revision can be estimated in:

Yearly methane revision = 600 €

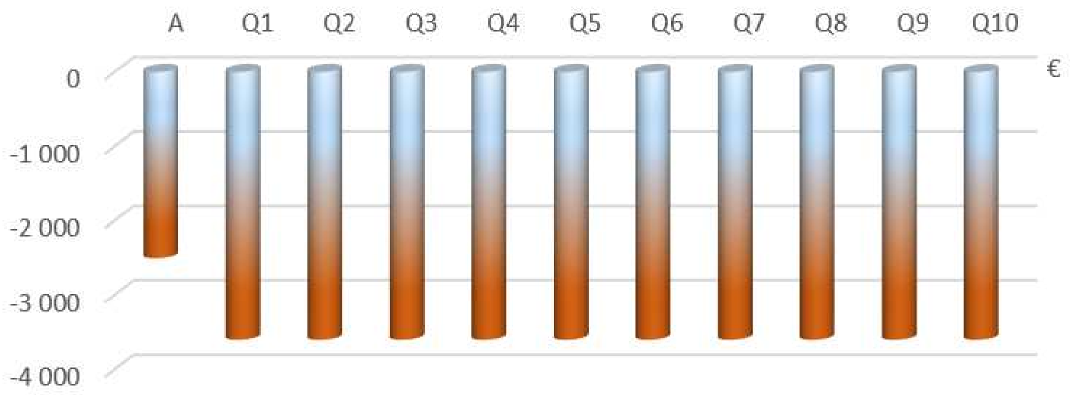
It can be estimated as 10 years the period that will be necessary to undergo the revision of detectors.

Just by leaving a vent hole in each of the shafts and/or on the ventilation shafts, according to the results of the Ventgraph simulation, when they will be sealed, this will help a lot in fighting against the risk of methane accumulation in the basements of buildings within the mining area.

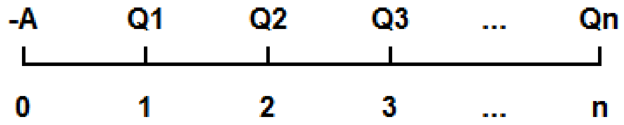
Regarding Radon the likelihood for emission of gases to the surface was rated with an "D", as it is expected to occur regularly under normal circumstance. In case that it happens, the impact will be moderate (monetary loss can be estimated between 60,000 € and 300,000 €), and thus, the risk will be medium so specific measures should be adopted. To minimise the existing risk, it is necessary to perform measurements in soil gas in mining and post-mining areas. The cost can be estimated in:

Yearly radon revision = 3,000 €

Considering these questions, the next Figure shows the cash flows for the gas risk treatment cost.



Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 2,500 €

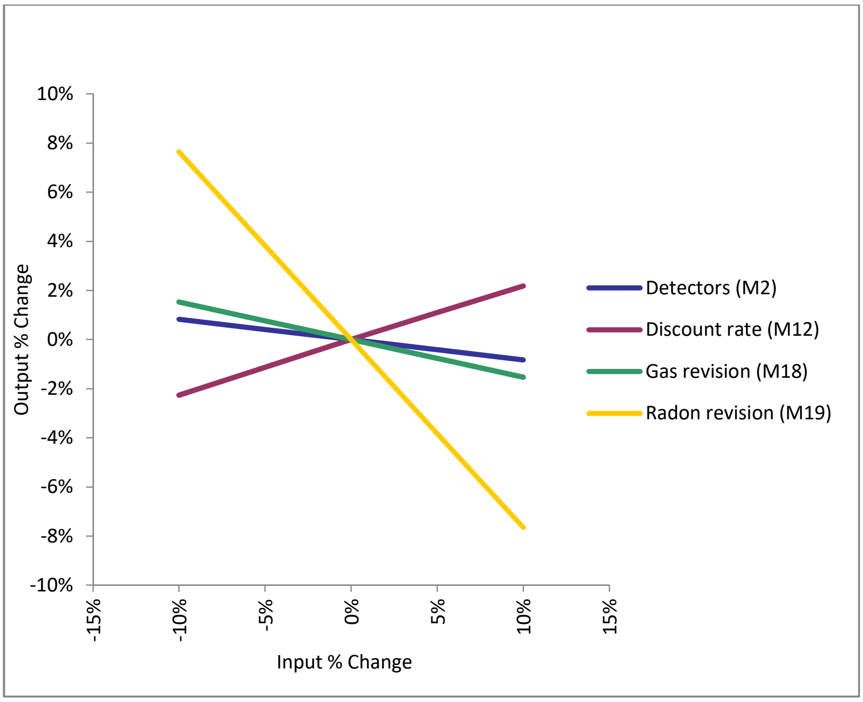
Q1, Q2, Q3, Q4, Q5… Q10 = - 600 € – 3,000 € = -3,600 €

k = 5% ; n = 10

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 gas risks will be:

NPV = - 30.298 €

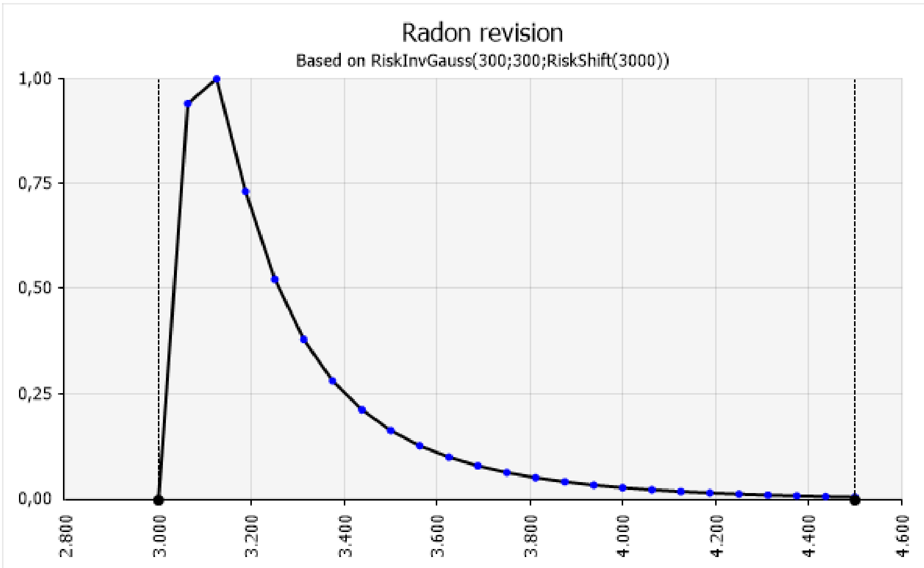
In order to estimate to which cost the NPV is more sensitive, a sensitive analysis was developed by means of allowing a ±10% in every variable. The spider graph obtained was the following one:



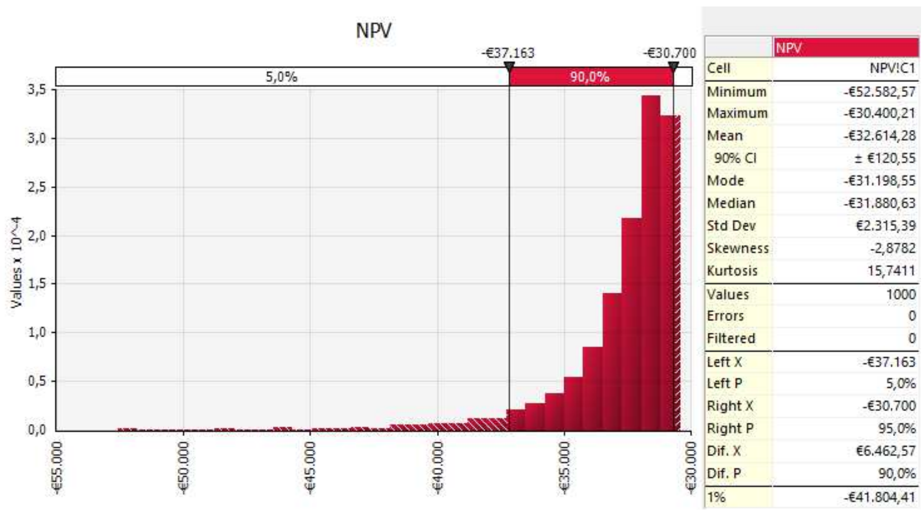
Economic evaluation: Uncertainty analysis

In this case, the NPV has almost the biggest sensitivity to the cost of the yearly radon revision. As it was said before, we will not consider in the calculations possible variations of the discount rate. Nevertheless, in this case the NPV presents quite low sensitivity to it.

In order to undergo an uncertainty analysis, the yearly costs of radon revision will be well modelled by an inverse Gaussian distribution, also called Wald distribution, centered in 3,000 € with parameters Mu = 300 and Lambda =300, in order to represent possible bigger prices but with a low probability:

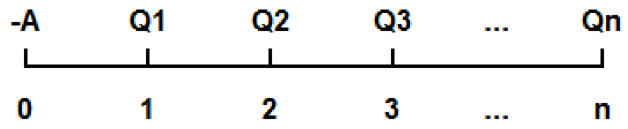


On the other hand, the detectors will be modelled again by triangular functions with parameters varying a 10% up and down. Running the Monte Carlo analysis, the NPV will be the following one:



So the NPV distribution obtained has a mean of -32,614 €, a maximum of -30,400 €, a minimum of -52,583 € and a standard deviation of 2,135 €.

Complete treatment cost: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 450,000 € + 140,000 € +2,500 € = 592,500

Q1, Q2, Q3, Q4, Q5 = - 21,600 € - 60,000 € - 600 € - 3,000 € = - 85,200 €

Q6, Q7 = - 60,000 € - 600 € - 3,000 € = - 63,600 €

Q8, Q9, Q10 = - 600 € - 3,000 € = -3,600 €

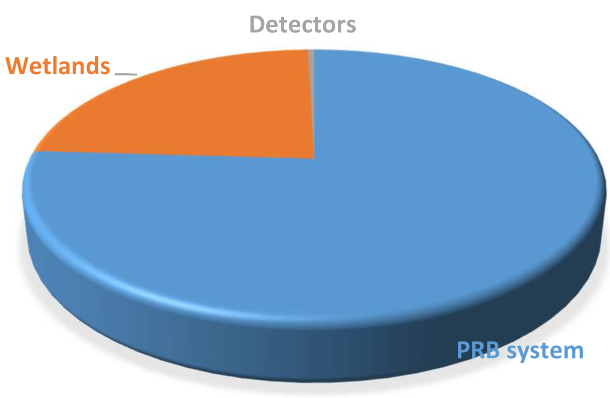
k = 5% ; n = 10

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 will be:

NPV = - 1.060.997 €

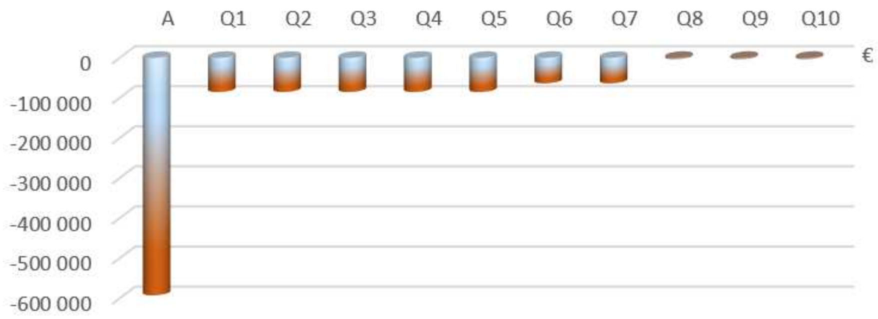
The distribution of the investments can be clearly observed in the following figure, with the CESR plant in first place and the aerobic wetlands in second place.

Thus, the investments needed to remediate the groundwater pollution risk are the most expensive of all.

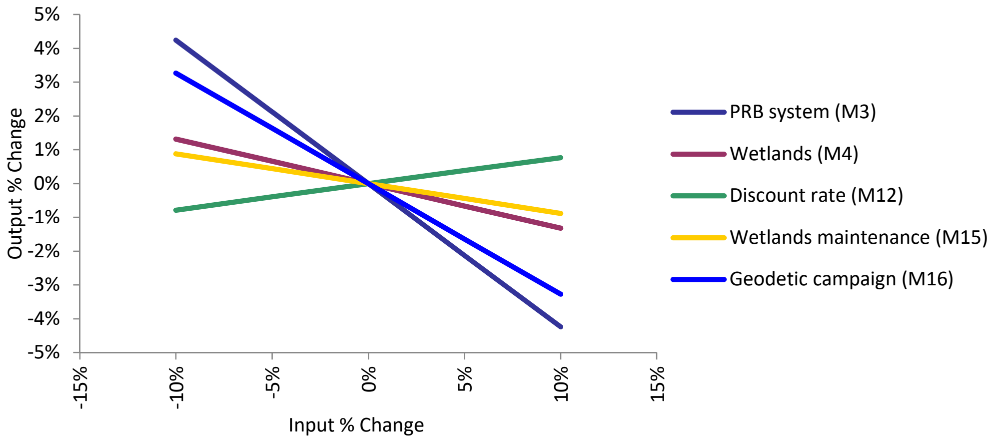


Complete treatment cost: Uncertainty analysis

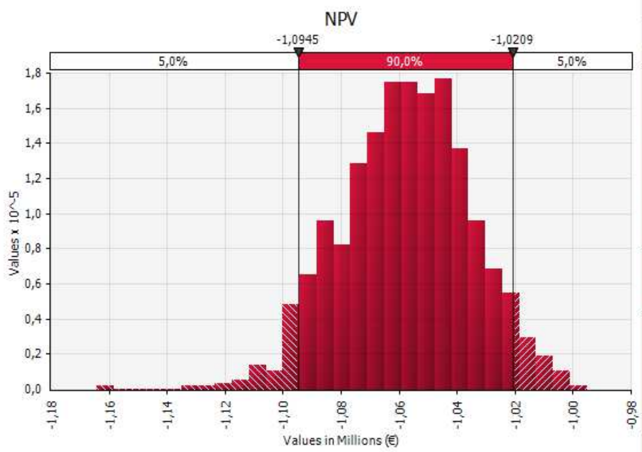
Addressing now the cash-flows, the following figure presents the different cash-flows during the 10 years considered:



The following spider graph clearly presents the PRB investment as the one to which the variable is more sensitive.



Running the Monte Carlo analysis, the NPV will be the following one:



	NPV
Cell	NPV!C1
Minimum	-€1.164.160,24
Maximum	-€995.134,15
Mean	-€1.057.318,04
90% CI	± €1.160,19
Mode	-€1.051.065,31
Median	-€1.056.765,45
Std Dev	€22.284,25
Skewness	-0,2121
Kurtosis	3,2369
Values	1000
Errors	0
Filtered	0
Left X	-€1.094.508,67
Left P	5,0%
Right X	-€1.020.856,26
Right P	95,0%
Dif. X	€73.652,41
Dif. P	90,0%
1%	-€1.109.968,65

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 standar deviation of 22,284 €.

Conclusions

In first place, the ground water risk treatment costs were analysed. The pollution treatment 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.

Secondly, the surface water risk treatment costs were analysed. Only one pollution treatment options should be installed in this case: 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 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. This aspect will be considered later on.

In third place, the ground movement risk treatment costs were considered. Only a yearly geodetic campaign should be developed during seven years. The mean NPV was -331,868 €.

Finally, the gas risk treatment costs were analysed. Installing gas detectors that will be revised on a yearly basis was the only treatment considered, as well as yearly methane and radon revisions over a period of 10 years. The mean NPV obtained was -32,614 €.

Concluding, the mean cost analysis and financial provisions required for closure and post-closure for the selected PGG mines are estimated in -1,057,318 €. Nevertheless, according to the uncertainty analysis, this value could reach up to -1,164,160 €, so a conservative amount of -1,200,000 € will be considered.

However, something has to be made regarding the high impacts that the different discharges will produce regarding the amount of sulphates and chlorides.

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, it should be possible to use these quantities in order to estimate a financial provision that, although cannot be used to fight against these hazards, it will 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 it can be compared with the biggest of major impacts, that is, 600,000 € in each case. Thus, a provision of 1,200,000 € could compensate in some way the impact caused.

As it could be seen, costs related with water pollution treatment are the most significate. Thus, water can be considered as the critical environmental risk when addressing the closure of a mine in the Silesian coal basin.

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, this amount does not consider the costs related with water pumping or with the sealing of the shafts.

Appendix 2: Case Study (Spain)

Model: Conceptual model

During the implementation of the MERIDA project the analyses of the flooding of underground excavations have been performed using three new methods, which were:

- Pore pressure change method,
- Hydrostatic pressure change method,
- Mediums density change method.

Performing a 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:

- the pores in the soil (rock) are completely filled with water, but the soil (rock) is above the groundwater table, in which case the volumetric weight is given by:

$$\gamma_{sr} = (1-n)\rho_s g + n\rho_w g \quad [kN/m^3]$$

where:

γ_{sr} is the volumetric weight of the soil (rock) above the water table;

n is the porosity of the soil (rock);

ρ_s is the specific density of the soil (rock);

ρ_w is the specific density of water.

- the soil (rock) is located below the groundwater table, in which case:

$$\gamma' = (1-n)(\rho_s - \rho_w)g \quad [kN/m^3]$$

where:

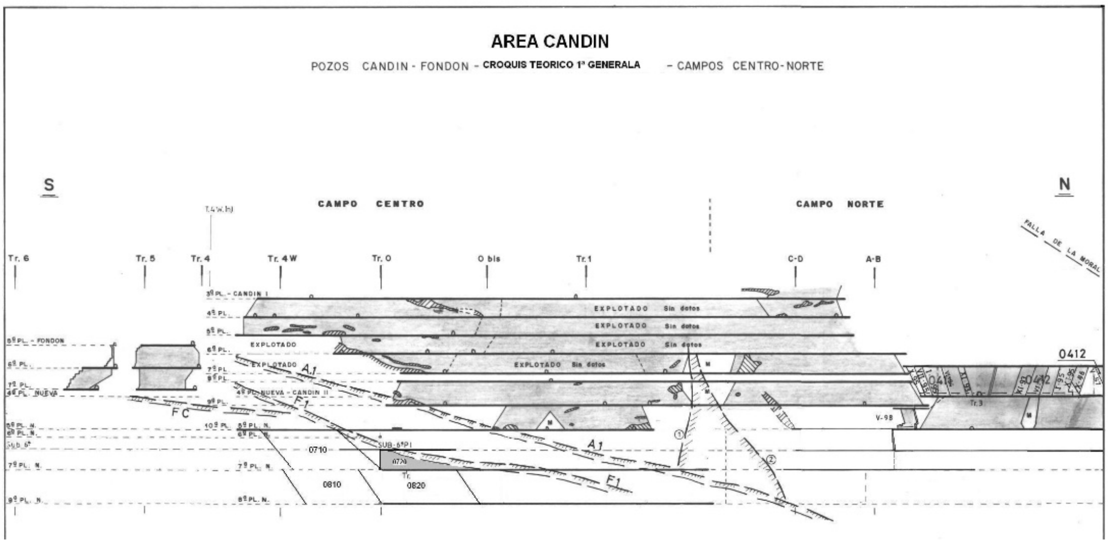
γ' is the volumetric weight of the soil (rock) above the water table.

In this case, the pores are also filled with water, but according to Archimedes' principle, the weight of soil (rock) will be much smaller than the weight of soil (rock) located above the water table.

This results from the fact that water does not add weight to the granular soil structure, and additionally causes its buoyancy. This method offers simplicity of use and has a strong geomechanical basis.

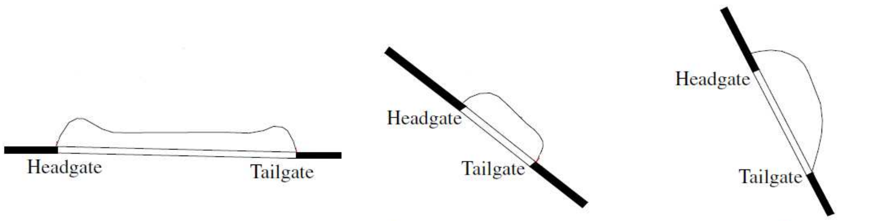
Model: Numerical model

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 idealized physical system, which, for the needs of the analysed process, will represent 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 have been performed for homogeneous model. Figure below shows example geological cross-section in the Candin mine region.



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. The characterization of mining extractions performed in mines belonging to the Hunosa company has proved that, due to geological conditions (in relation to the position of coal seams), mines perform extraction from walls at high inclinations (from 50 to 85º).

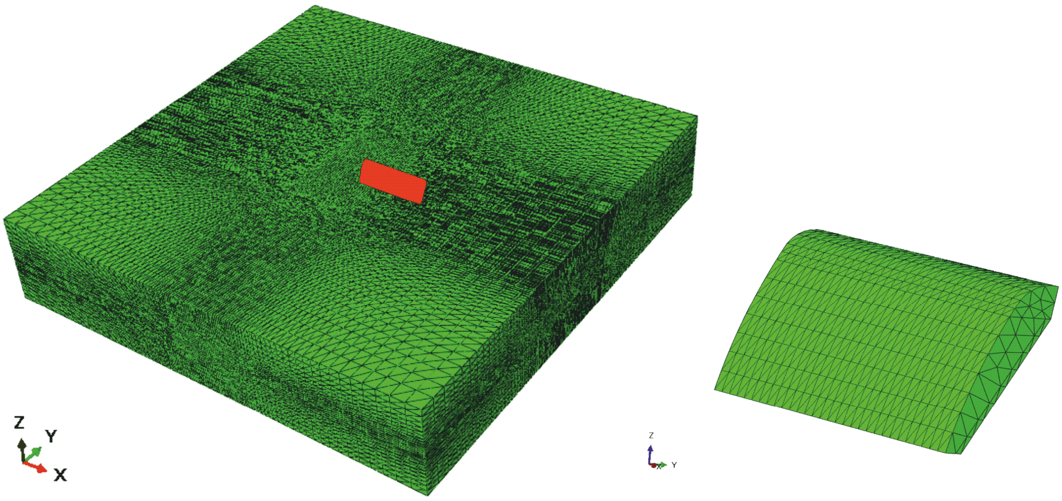
These operations result in disrupting the initial state of stress and strain of rock mass, which leads to the generation of disturbed zones (a caved and fractures). Due to the nature of extraction performed in the mines of Hunosa (inclination of coal seams), the shape of the generated caved zone deviates significantly from the shapes of caved zones observed during longwall mining with no inclination (or with a slight inclination). The figure below presents schematically the possible shapes of a caved zone depending on the inclination of the extracted seam.



(a) Flat or slightly inclined seam (b) Inclined seam (c) Steeply inclined seam

Because the area of the Candin mine is very large (approx. 5 985 million m3), 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. This is why in order to perform precise numerical simulation, a decision was made to divide the whole region into four parts.

Using prepared earlier information, the 3D numerical models using Finite Element Method, which represents analyzed region of the mine, have been prepared. When building a numerical model, it must be consist of a sufficiently large number of elements. It will ensure high accuracy and quality of results from calculations. Generated example model for part of Candin mine, with flooding zones marked in red, and cave-in zone is shown below.



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:

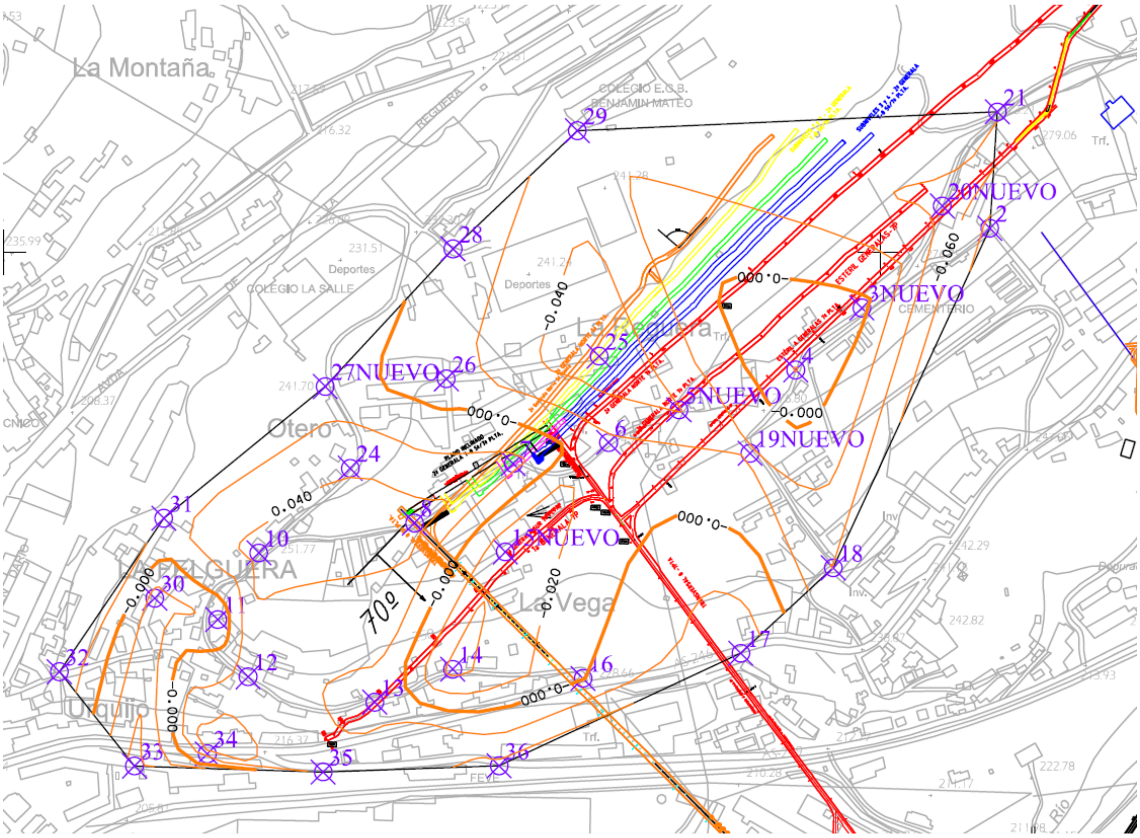
1. Simulation of the initial state of stress and strain.
2. Longwall panel exploitation, where the so-called equivalent elements with lower parameter values in a highly disturbed zone (a cave-in zone) were introduced into the model.
3. Goaf flooding simulation. The selected simulation was related to the change in the volumetric weight of the rock mass in the area of the mining goafs.

Model: Simulation results

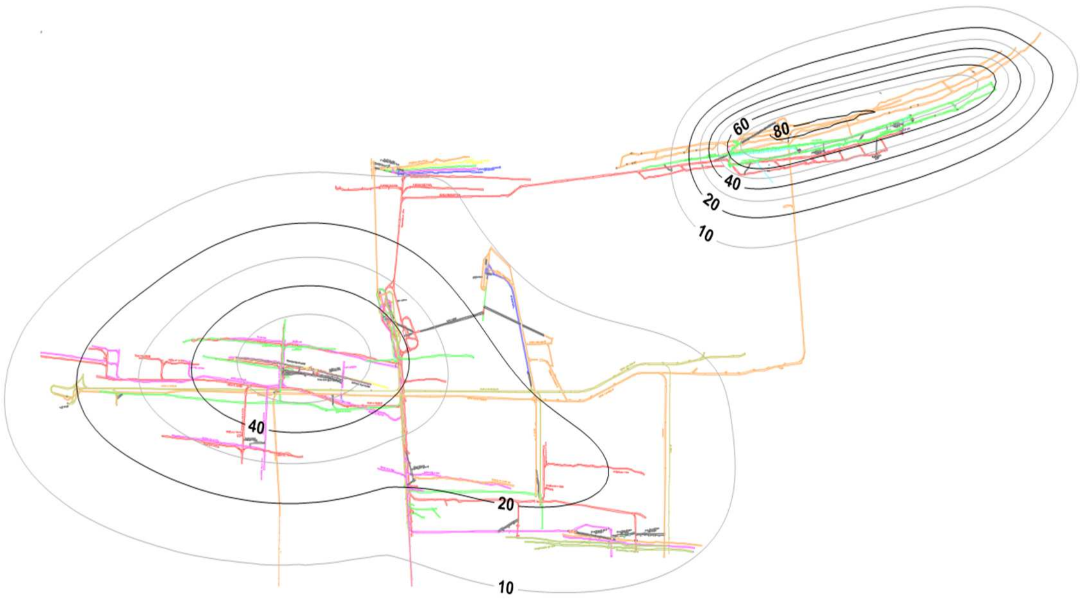
The results of the models allow obtaining the distribution of deformation indicators on the ground surface, such as displacements or stresses. In addition, distribution of these indicators in the rock mass can be achieved.

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

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. Figure below shows map with measurement point in Candín mine area.

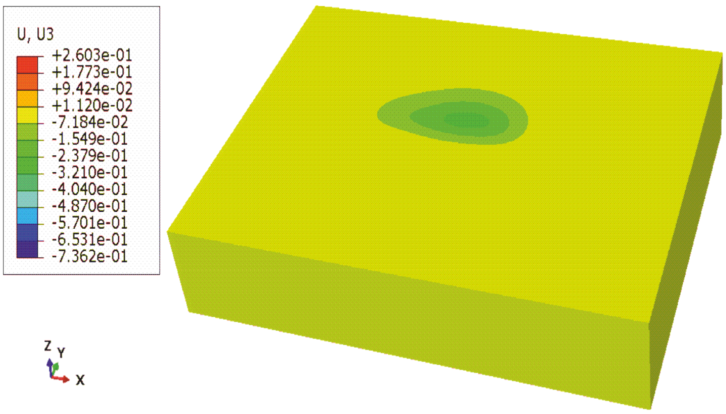


In the last step, the flooding of the mine is simulated. Calculation has been performed using medium's density change method proposed by the authors. Changing density of the material in excavation region, expansion of cave-in zone is achieved and the propagation of the vertical displacement from this zone up to the surface. The distribution of the ground surface deformation and rock mass deformation is obtained.

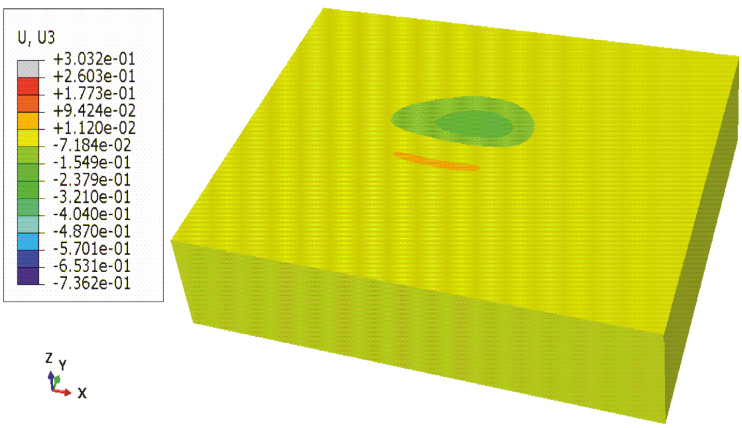


Figures bellow shows respectively change in vertical displacements for example model on the ground surface for post-mining state (a) and after flooding of goafs (b).

(a)



(b)



Risk assessment: 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.

The diagram of the surface hazards related with mine flooding is presented below.

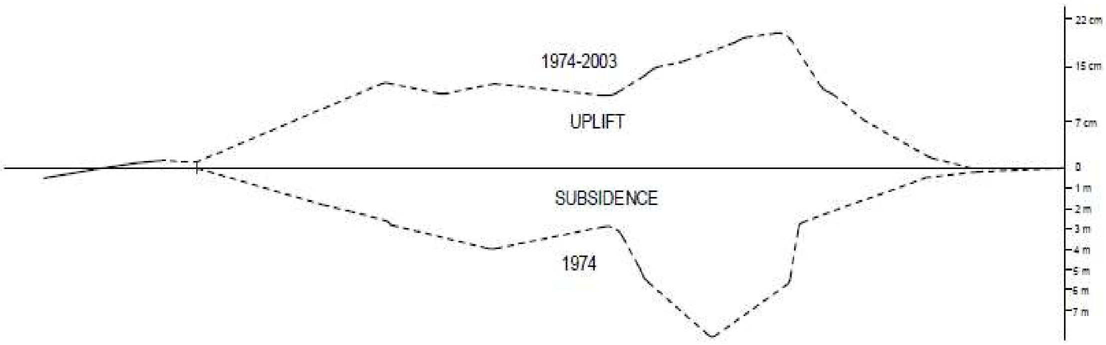
Continuous deformation

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 centimeters) 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 define as small or very small in comparison to discontinuous deformation.

Next figure shows the uplift and subsidence magnitudes of the surface (Pöttgens, 1985).



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.

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 neighborhood rocks, is the precursor process of water inrush.

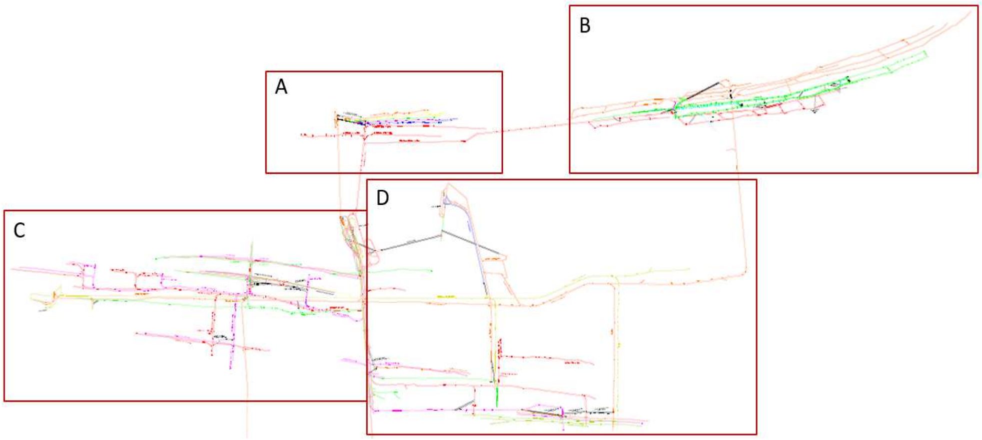
All presented threats, under appropriate conditions, can lead to visible surface deformations and as a consequence, damage to objects/civil structures located on the land surface and/or environment. In order, to determine the degree of hazard during the mine liquidation by flooding, risk stages were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

Risk assessment: Risk analysis

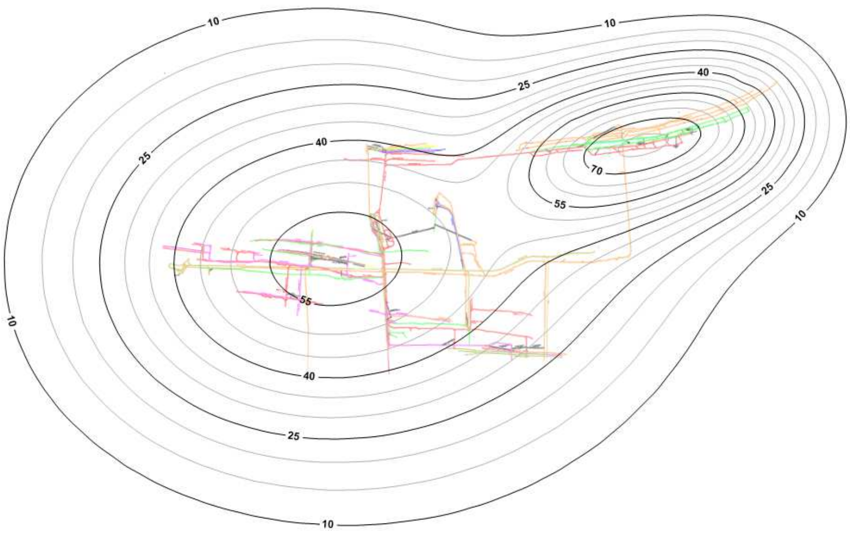
Uplift

The risk analysis considers the ground surface uplift during the closure of Candín mine, with flooding to the depth of 174 m.a.s.l.

To assess the risk associated with ground surface continuous deformation, the deformation indicators have to be estimated, i.e. uplift (vertical deformation). The analysis consider flooding of the Candin mine to the depth 174 m.a.s.l. The flooding areas are presented on the figure below.



Predicted uplift for Candin mine obtained using Sroka's method is presented bellow.



The flooding analyses have been performed using two methods. Mentioning only, 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 the first method, maximum vertical displacement of 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.

Fractures and cracks

The probability of discontinuous linear type deformations occurrence on the land surface is an extremely difficult task to accomplish.

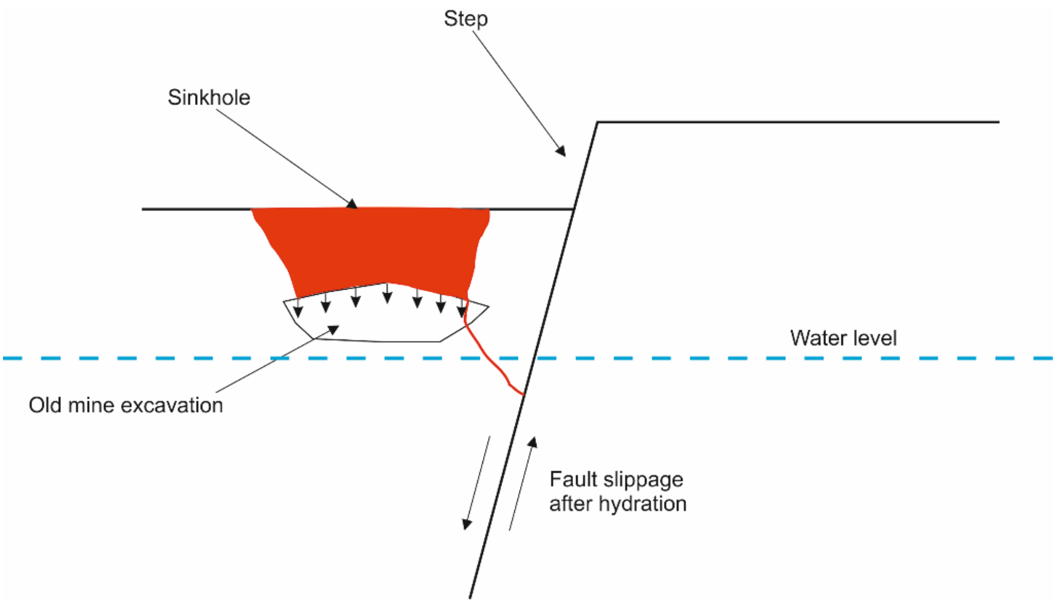
In addition, the influence range of this type of deformation is hard to predict due to insufficient data and information on the nature of the fault (e.g. fault permeability, fault filling and its physical parameters, fault roughness and others).

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.

Authors experience dealing with the problem related to discontinuous surface deformations, indicate that flooding may induct some sort of incursion in fault region, which is a result of long-lasting multiseam mining operations in these areas affected by some distortion (such as mine tremors, mine heading advancing pressure etc.).

Sinkholes

The situation when the sinkhole can appear during flooding operations is the one in which the slippage of the fault appears.



The formation of such deformation is favored by the existence of shallow old mining exploitation in a short distance from the fault.

Due the lack of information about the existence of shallow excavations in the flooding area of the mine, the risk analysis could not be carried out.

Nevertheless, if the information about the existence of old shallow excavations will be confirmed, their possible activation and sinkholes appearance should be taken into account, especially due the depth of flooding in Candin mine (174 m.a.s.l.).

Risk assessment: Risk evaluation

Uplift

As it has been mentioned in the risk identification section, the first 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.

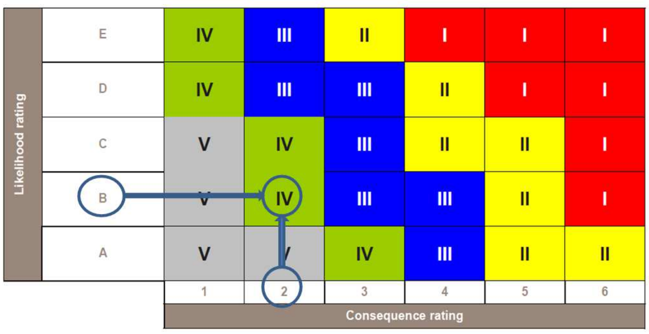
The authors' experience in the field of rock mass deformations caused by the mine flooding and analyses, show a small risk of damage to buildings on the ground surface and hazards related to environment by continuous deformations.

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 when only continuous deformations are taken into consideration.

The results obtained by applying the proposed methodology of risk assessment are presented below.

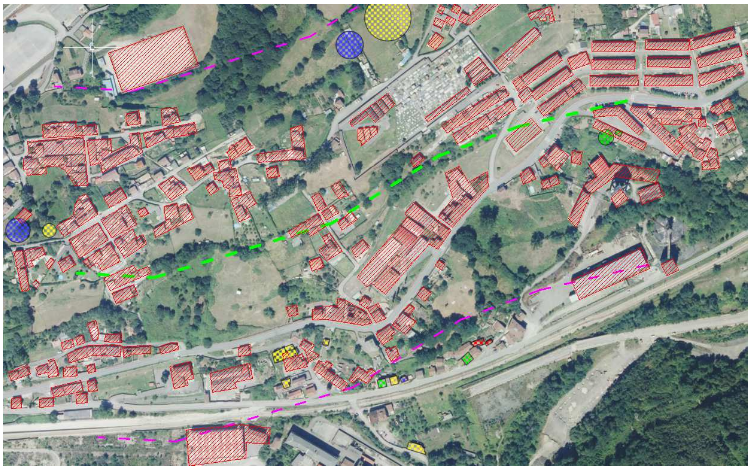


B	UNLIKELY: Not likely to occur in normal circumstances
2	MINOR: Very low impact; loss between 10,000 € and 60,000 €
IV	LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.

Fractures and cracks

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 exists 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 located on the land surface.

The figure bellow illustrates a part of a region disturbed by geotechnical faults (F1 fault – green dashed line). From the experience and research carried out by the authors, a zone of potential impact of the fault on objects located on the ground surface has been marked by dashed magenta line. 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 are presented below.

Likelihood rating	1	2	3	4	5	6
E	IV	III	II	I	I	I
D	IV	III	III	II	I	I
C	V	IV	III	II	II	I
B	V	IV	III	III	II	I
A	V	V	IV	III	[illegible]	II

Consequence rating

B UNLIKELY: Not likely to occur in normal circumstances

5 SEVERE: Serious impact event; loss between 600,000 and 2,000,000 €

II HIGH: Strong investments will be necessary in order to control the risk. Measures should be adopted in a shorter period of time than with the medium risks

Risk assessment: Proposed treatments

Uplifts

To minimise the existing risk, it is necessary to take steps to measure constantly deformation of the ground surface during the mine closure. In addition, in parallel with it, required is to monitor all the objects located on the surface, especially long structures, such as pipelines, warehouses, etc. Monitoring of the structures should be understood as:

- Measurement of object strains, displacements, tilt (especially long buildings),
- Regular objects inventory in search of damages (scratches, cracks).

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

Measurements of deformation of the land surface and objects can be carried out using traditional measurement methods, which are geodetic measurements. Levelers are used for this purpose.

To monitor surface deformation, advanced satellite technologies can be used to enable this task to be carried out effectively. DInSAR - Differenal Synthec Aperture Radar Interferometry is a modern technology of remote deformation measurement from a satellite level.

Fractures and cracks

Discontinuous deformations appear on the land surface 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.

The most important influence is the change of support conditions under some parts of foundations. It can be related with uneven settlement of a part of building or creation of 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, in the area of the flooded Candín mine, it is necessary to take steps to measure periodically deformation of the land surface.

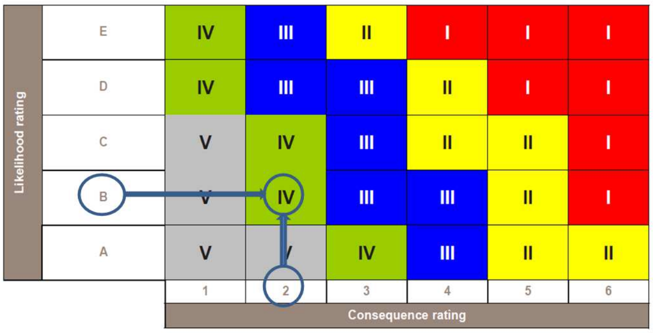
If the newly designed buildings are taken into consideration, it is necessary to introduce information on the possibility of discontinuous deformation occurrence in such area in the land use plan.

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.

Risk assessment: Performance forecast

Uplifts

The implemented solutions aimed at minimizing the risk will reduce the likelihood of mining damage, but this will not change the level of risk.



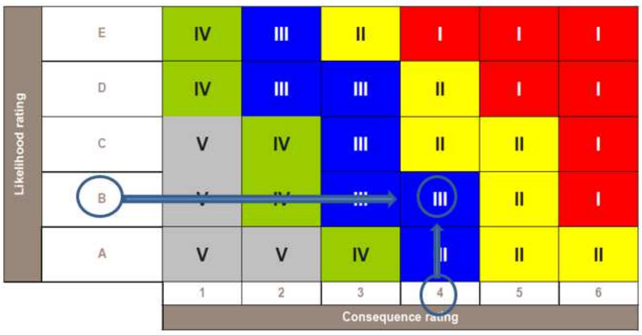
B UNLIKELY: Not likely to occur in normal circumstances

2 MINOR: Very low impact; loss between 10,000 € and 60,000 €

IV LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.

Fractures and cracks

The proposed treatments will reduce the likelihood of damage to ground and underground infrastructure. Implementation of appropriate monitoring and proposed protection methods will lead to a reduction in the effects of liquidation process carried out in the mine and a quick response to the appearing rock mass deformations and should change the level of risk.



B UNLIKELY: Not likely to occur in normal circumstances

4 MAJOR: Significative impact; loss between 300,000 and 600,000 €

III MEDIUM: Specific measures should be adopted and implemented in a short period of time

Economic evaluation: Cost evaluation

According to Deliverable 4.2, the likelihood for uplifts was rated with a “B”, as this kind of rock mass deformation is not likely to occur in normal circumstances. In case that it happens, the impact will be minor (monetary loss can be estimated between 10,000 € and 60,000 €), and thus, there is no need to change the control, although not very expensive measures should be implemented and periodic monitoring should be considered.

To minimise the existing risk, it is necessary to take steps to measure constantly deformation of the ground surface during the mine closure. In addition, in parallel with it, required is to monitor all the objects located on the surface, especially long structures, such as pipelines, warehouses, etc. 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).

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

Measurements of deformation of the land surface and objects can be carried out using traditional measurement methods, which are geodetic measurements.

Thus, annual campaigns should be developed during the flooding and during the following seven years, as it is two years more than the maximum period of subsidence, being a good safety margin until the end of the uplift.

The cost of an annual geodetic campaign covering the area of influence can be estimated in:

Yearly geodetic campaign = 45,000 €

The implementation of appropriate monitoring methods will lead to a reduction in the effects of liquidation process carried out in the mine and a quick response to the appearing rock mass deformations. The result will be a reduction in mining damages.

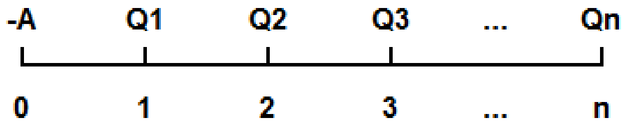
In second place, the likelihood for fractures and cracks was rated again with a “B”, as this kind of rock mass deformation is not likely to occur in normal circumstances. In case that it happens, the impact will be severe (monetary loss can be estimated between 600,000 and 2,000,000 €, and thus, strong investments will be necessary in order to control the risk. Measures should be adopted in a shorter period than with the medium risks.

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.

The only possible action is to monitor the affected area, something that can be considered as included within the annual geodetic campaign for uplifts.

Finally, and due the lack of information about existence of shallow excavations in the flooding area of the mine, the risk analysis about sinkholes could not be carried out.

Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 0 €

Q1, Q2, Q3, Q4, Q5, Q6 and Q7 = - 45,000 €

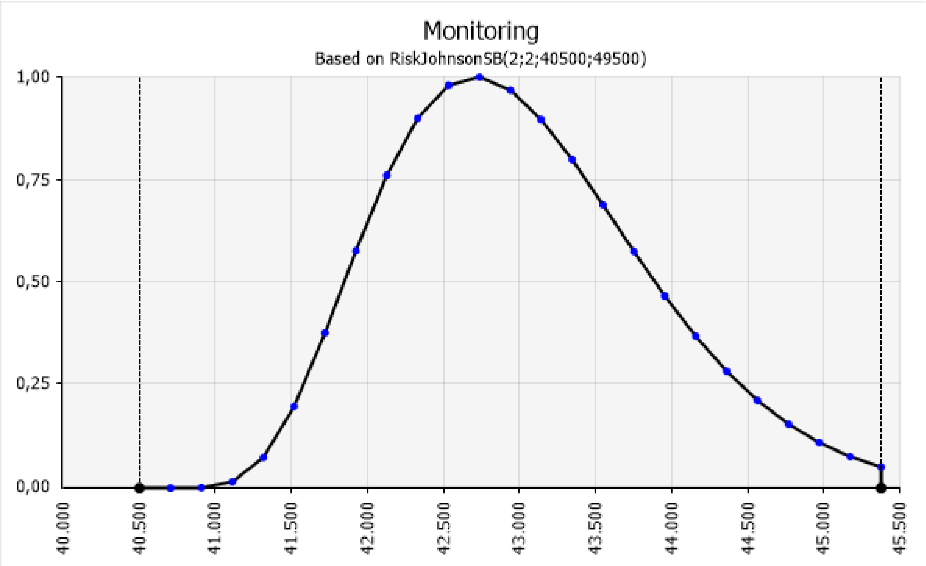
k = 5% ; n = 7

Calculating the Net Present Value in order to determine the financial provisions required for closure and post-closure regarding groundwater risks will be:

NPV = - 260,387 €

Economic evaluation: Uncertainty analysis

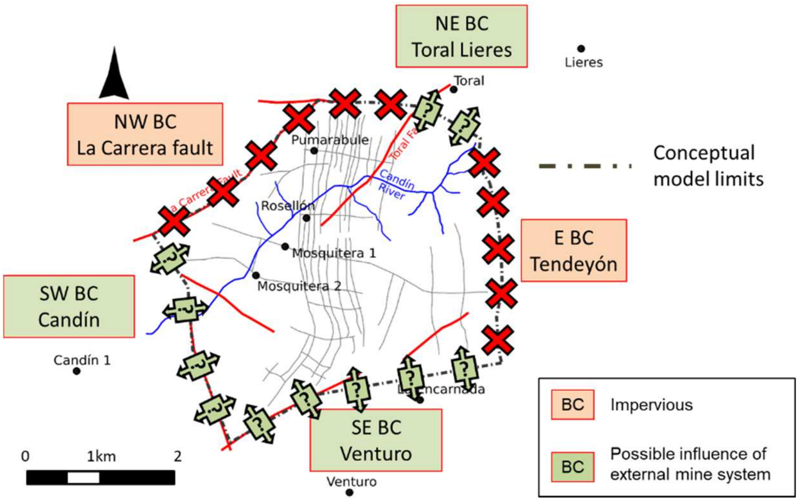
In order to establish which distribution function will be selected for the global NPV estimation, a bounded Johnson distribution will be selected for the yearly geodetic campaign cost. It is used commonly for the modeling of expert opinion, project management and cost analysis. It will have the following parameters: α1=2, α2=2, a=40,500 and b=49,500, with static value 45,000.



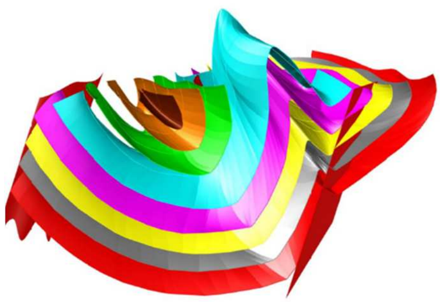
With this distribution function the NPV will be -248,899 €, with a maximum of -237,529 €, a minimum of -267,467 and a standard deviation of 5,050 €.

Model: Conceptual model

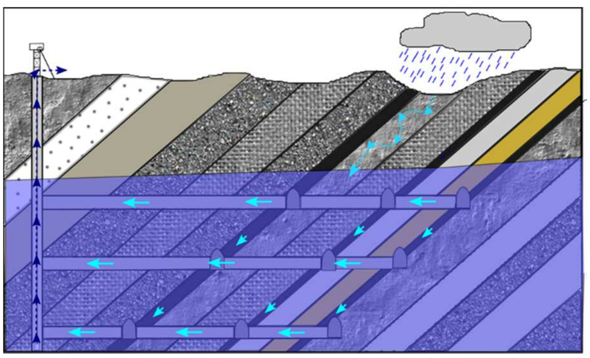
As main premise, the model must include the extension of the mine workings of the mines and the surrounding massif. However, to build the numerical model, the total volume has to be delimited identifying hydraulic limits where an appropriate boundary condition is applied.



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

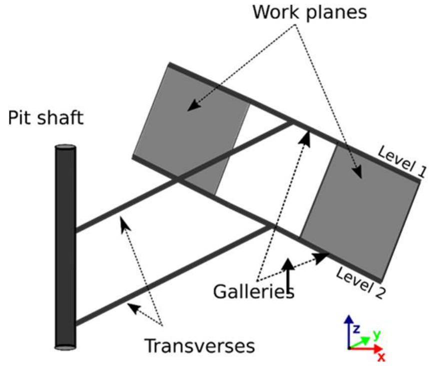


The model assumes that the mine workings act as an extensive network of drains that collects the water from precipitation recharge. The water infiltrates from the surface and flows through the massif to reach the open voids of the mine. Because the height of the water level in the mine must be maintained with artificial pumping, water flows by the galleries to the shafts where is extracted and discharged to the surface.

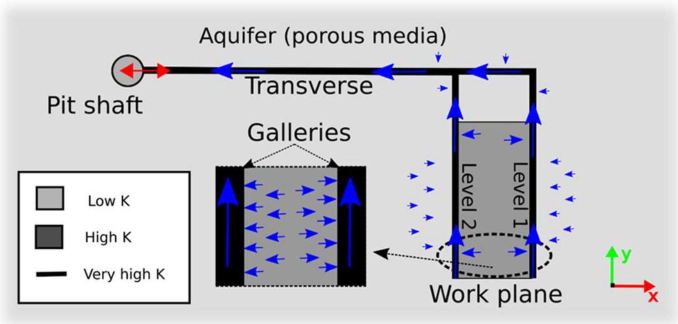


Model: Numerical model

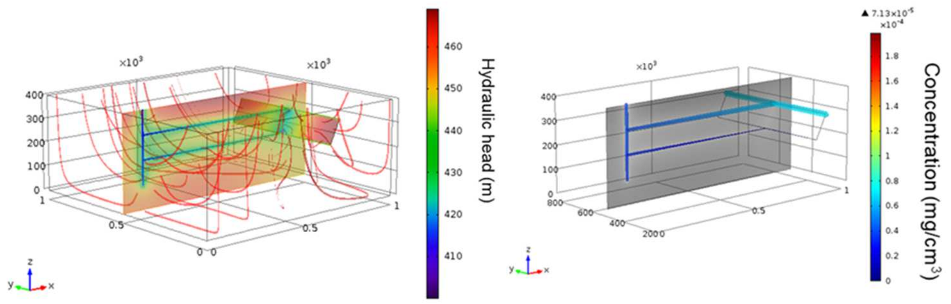
The numerical model is expected to include discrete elements that represent the mine workings such as galleries, shafts and working exploitation planes embedded in a massif where porous media flow takes place. The vertical shaft allows access to levels that connect with the coal exploitation zones with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



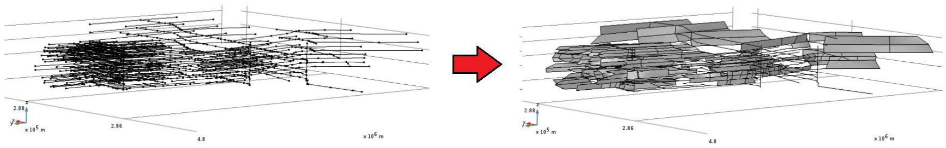
The physical laws that govern water flow in the elements of the mine are different. Two main processes must be coupled, but assuring continuity and conservation of mass: free water flow in the mine workings and porous media flow in the massif and filled working zones. A geochemical transport model has been coupled to the flow model to evaluate the concentration of species at the shaft (discharge point).



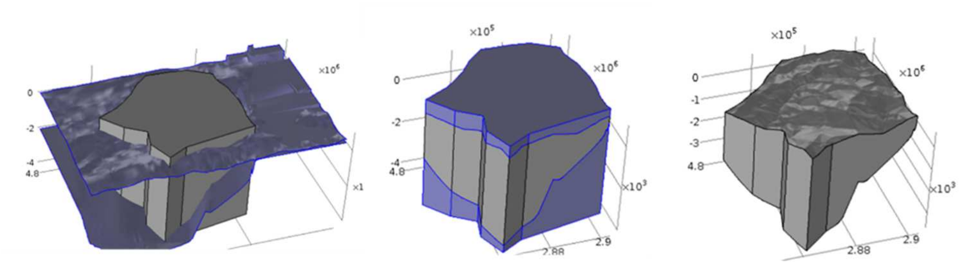
As a previous step to the fully implementation of the real mine and the study area in the numerical software, COMSOL Multiphysics, the elements and physics involved in synthetic numerical models were studied. These models aim to study the capabilities of the simulator in a similar mine type geometry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



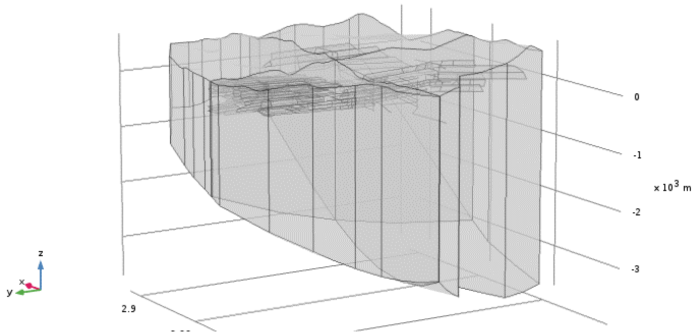
Underground mine workings represent a complex geometry that cannot be directly implemented into the numerical simulator from the original mine plans. Surfaces representing working plans were joined to one-dimensional elements that represent galleries and shafts to form the complete network of mine voids.



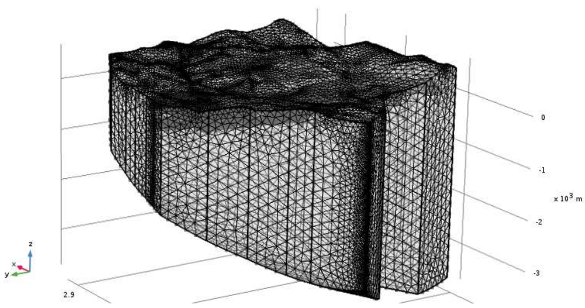
The construction of the final model requires the definition of a volume limited by the boundaries defined in the conceptualization stage. This is the volume in which the mine geometry is embedded and where porous media flow will take place. The building of this volume was conducted using AutoCAD and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



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.

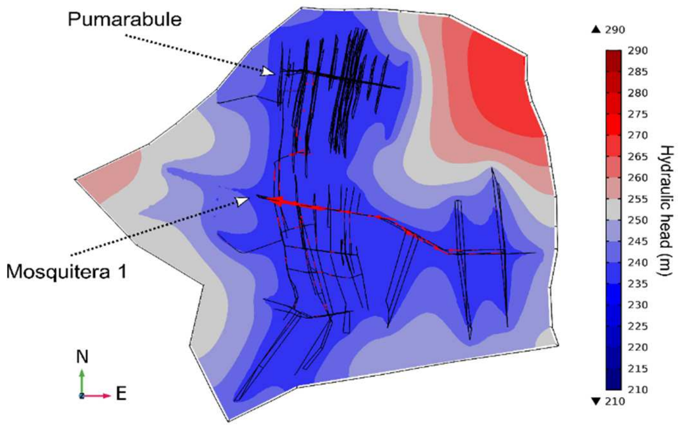


Then, parameters are assigned to the domains and the model can be meshed for running and extractions of results.

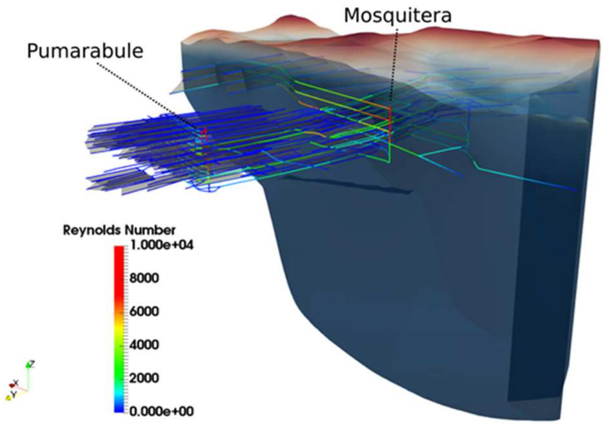


Model: Simulation results

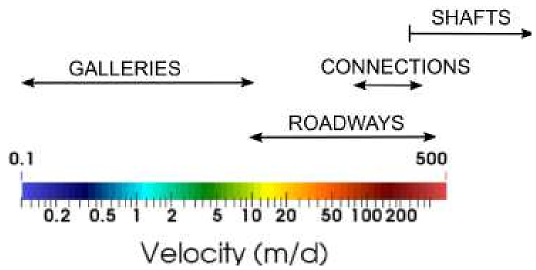
The results of the models allow to obtain the spatial distribution of hydraulic variables of interest such as hydraulic heads, water velocities, discharges or flow regime in the mine open voids. In first place, the influence of the mine is shown in the depression of hydraulic heads near the workings,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



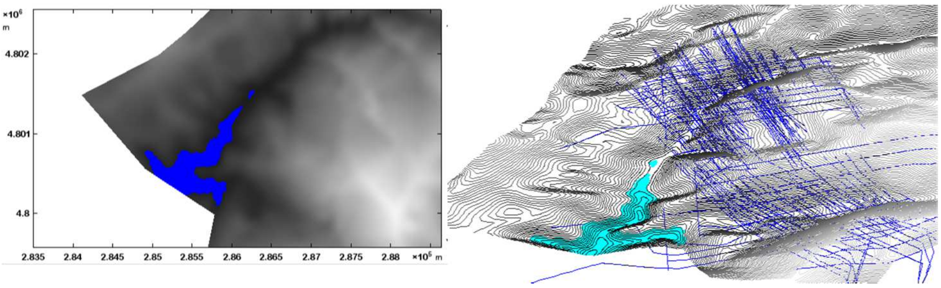
Secondly, Reynolds' numbers were utilized to indicate critical zones in which flow would be turbulent and provide orientation about the limits of applicability of laminar flow laws (Re < 2000).



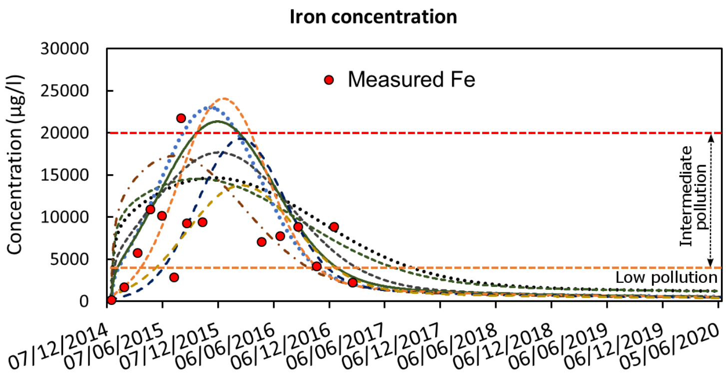
A classification of ranges of calculated velocities in the mine voids was done. These values agree with results from tracer tests in the literature and show the very high variability of velocities in the mine.



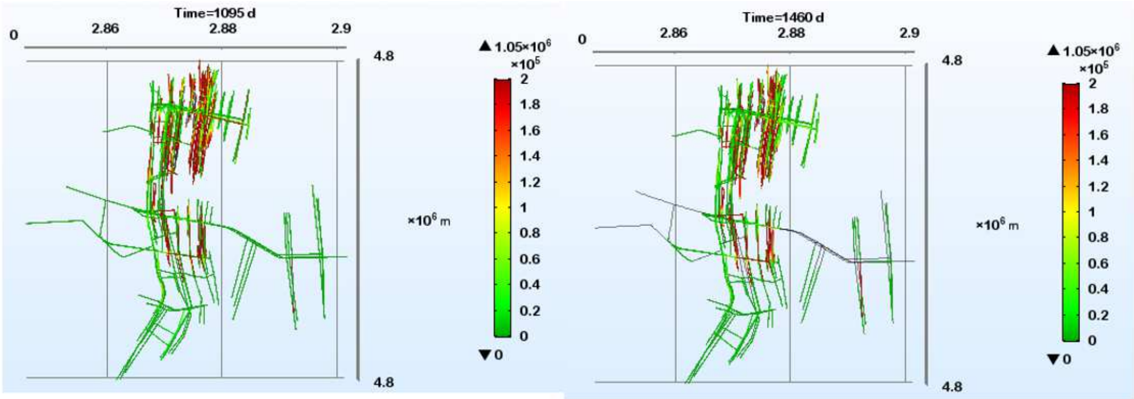
Results of inundation risks should be analysed in terms of groundwater flooding, which occurs when the water table in permeable rocks rises above the ground surface. The very low permeability of the carboniferous unaltered massif reduces the possibility of groundwater flooding, but a potential area of discharge has been identified in the Valley of Candín River.



Also, 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. 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, such as Fe and SO4.



High levels of contamination after four years happens only in galleries where water velocities are very low, so the flushing of the polluted water is slower. 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.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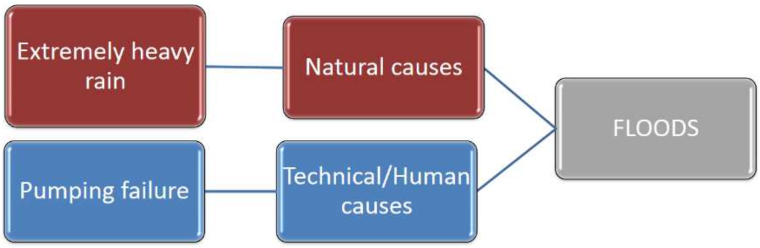
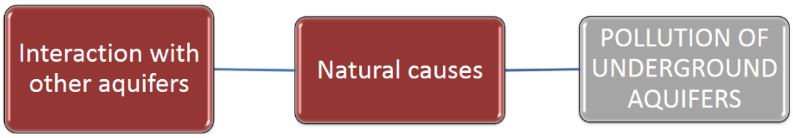
4.8
4.8
▲1.05×10⁶
×10⁵
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
▼0
×10⁶ m

Risk assessment: Risk identification

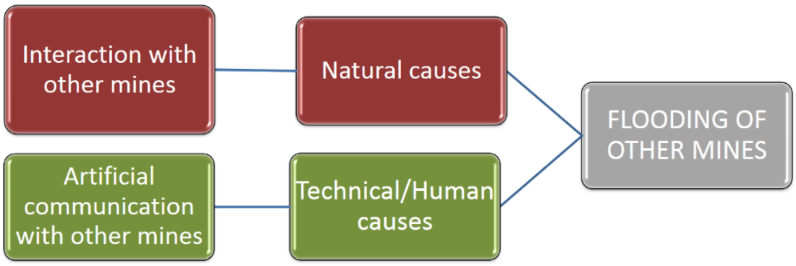
When analyzing the floods effect, three different sub-effects were considered together in the analysis: modification of flows, appearance of humid zones and floods (violent or not), as all of them imply an undesired flooding level of the mine water. In order to simplify the model, technical and human causes were considered together and the risks were reduced to one that comprises all the rest: pumping failure, as it can be considered an effect of the rest of possible causes: control system failure, mechanical failure, electrical failure, sabotage and maintenance error.



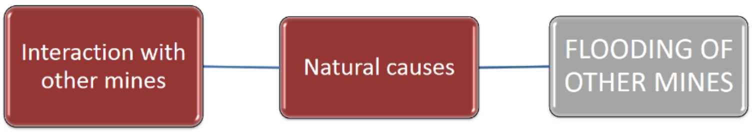
Analyzing the pollution of underground aquifers, again technical and human causes were considered together. Moreover, the artificial communication with other aquifers, although something that may happen, it is very improbable, so it does not appear in the following figure that represents a simplified tree formulation of cause-and-effect analysis for the pollution of underground aquifers effect.



When considering the flooding of other mines effect, again technical and human causes were considered together.



Nevertheless, as the artificial communication with other mines was not possible, as there are no other mines that are being exploited currently in the surroundings, the following figure presents a simplified tree formulation of cause-and-effect analysis for the flooding of other mines effect.



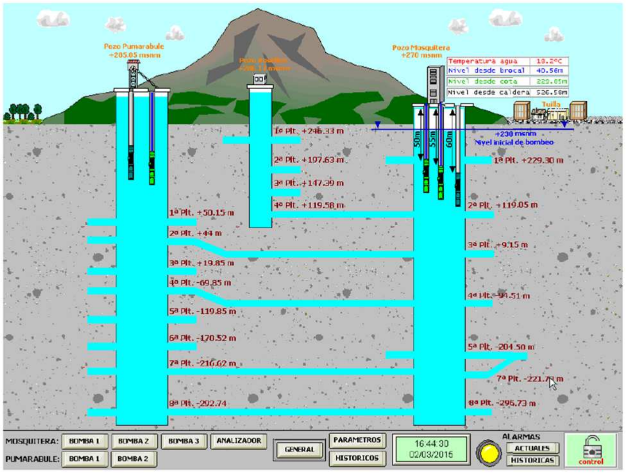
Risk assessment: Risk analysis

Floods: extremely heavy rain

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 (3 in Mosquitera and 2 in Pumarabule) to maintain the security level:

- Mosquitera: three 37 kW pumps with a nominal flow of 225 m^3/h each.
- Pumarabule: two 55 kW pumps with a nominal flow of 240 m^3/h each.

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



The historical pumping data that was available from Mosquitera and Pumarabule mines (since 1995) was extracted, as well as precipitation data from Oviedo meteorological station, which is located about 15 km from the study area.

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, the potential surface discharge area has been evaluated. 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.

The Candín River Valley is situated between 235 and 250 m.a.s.l. The area with the bigger probability is where the Candín river collects the waters from the Braña stream. Besides, 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.

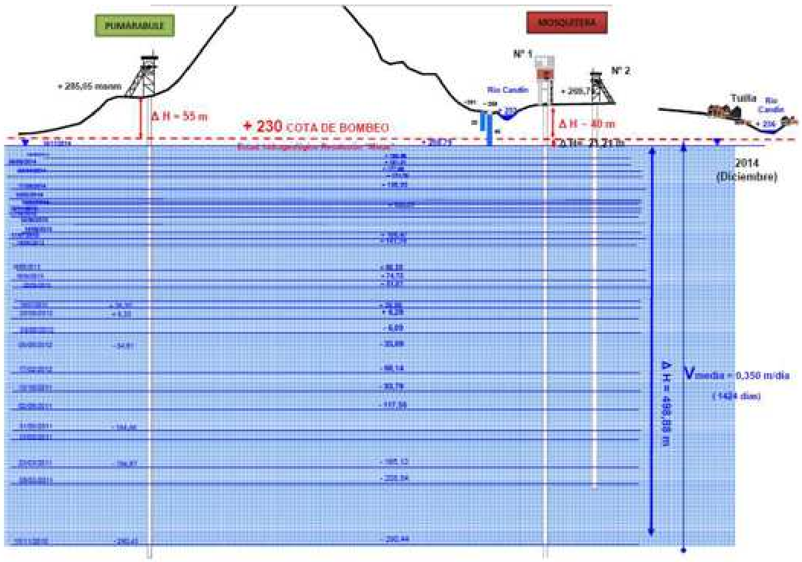
Thus, it was evaluated also a potential risk accounting for a sudden rise of water level in the shafts, that would be critical, as no buffer volume such an intermediate unflooded floor would be available in Mosquitera to impede fast discharge to the surface.

Floods: pumping failure

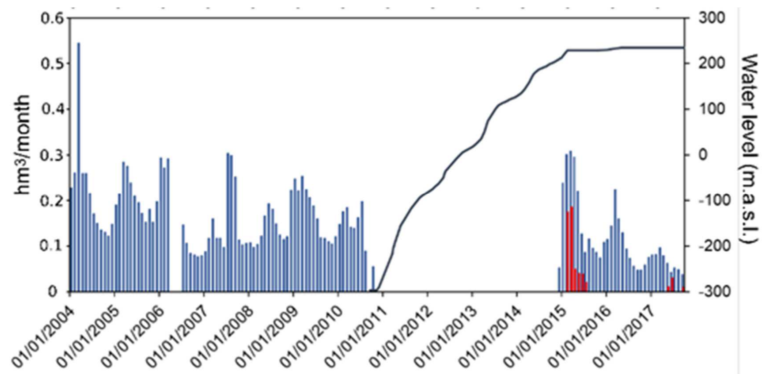
On 26 October 2010, Hunosa stopped the pumping in Mosquitera and Pumarabule pits. The groundwater rebound took about 4 years.

The total amount of flooding days was 1,424, with a flooded range of 498.88, thus giving an average flooding speed of 0.350 m/day. Nevertheless, it has to be considered again that no buffer volume such an intermediate unflooded floor is available in Mosquitera to impede fast discharge to the surface.

The following figure presents the different stages that were monitored during the flooding of Mosquitera and Pumarabule mines, as well as the situation of Candín River in its lower elevation.



The time evolution of water levels as well as the monthly pumping in Mosquitera and Pumarabule mines are presented in the next figure.



There are five pumps installed within the pumping system, in case one of them fails, the pumping capacity will only be diminished by an approximately 20%. In case that all of them fail to work, e.g. in the case of an electrical failure, a system control failure or a sabotage, it will take almost three days for the water to increase in one meter the actual level with the average flooding speed of 0.350 m/day.

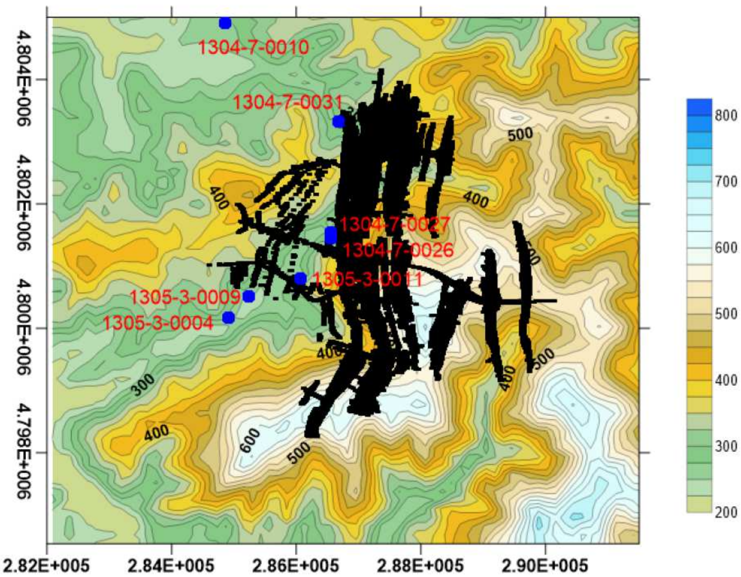
Pollution of aquifers

Regarding the pollution of aquifers, there are seven water points close to the study area in which the interaction with the mine water has to be studied.

The coordinates and the rest of their available information is presented below:

Code	Kind	Place	UTM X	UTM Y	Level (mosl)	Depth (m	Water depth (m)	Geological age	Use	km3/year	Working days/year	Aquifer system
1305-3-0004	Spring	Langreo	284912	4800163	240			Carboniferous	Water supply to urban areas	8	365	Mountain limestone Cántabro-Astur
1305-3-0009	Spring	Langreo	285243	4800504	240			Carboniferous	Water supply to non-urban areas			Mountain limestone Cántabro-Astur
1305-3-0011	Pit with gallery	Langreo	286071	4800796	200			Carboniferous	Industry	91	30	Mountain limestone Cántabro-Astur
1304-7-0010	Drill	Siero	284861	4804906	280	39.0	4.00	Cretacic	Water supply to non-urban areas			Mesoterciary unit Gijón-Cangas de Onis
1304-7-0026	Gallery	Siero	286552	4801441	260			Carboniferous	Not in use			Mesoterciary unit Gijón-Cangas de Onis
1304-7-0027	Pit with gallery	Siero	286553	4801541	260	477.0	4.20	Carboniferous	Not in use			Mesoterciary unit Gijón-Cangas de Onis
1304-7-0031	Spring	Siero	286675	4803324	265				Water supply to non-urban areas			Isolated aquifer

The next Figure presents in the map the relative position of the water points as well as the plant projection of the mine workings:



In the water points that correspond to springs, as all of them have a level (240-265 m.a.s.l.) higher than the mine water level (235 m.a.s.l.), the elevation prevents polluted discharges from Mosquitera-Pumarabule mines. These are the water points: 1305-3-0004, 1305-3.0009 and 1304-7-0031.

The drill 1304-7-0010 is out of the model boundaries, thus there will be no influence from the Mosquitera-Pumarabule mines.

On the other hand, in the water points 1304-7-0026 and 1304-7-0027 that correspond to a gallery and to a pit with gallery respectively, the level of the water is considerably above the Mosquitera-Pumarabule mine water level. Moreover, both water points are not in use.

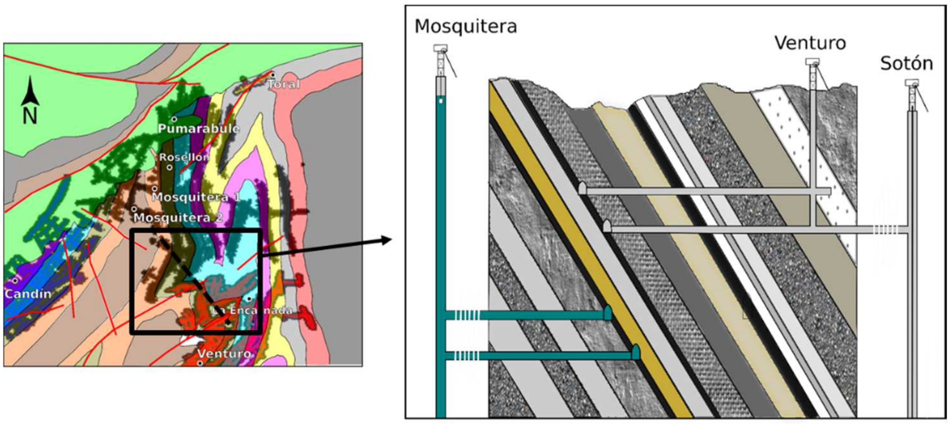
Flooding of other mines

Three mine systems in the area are close to Mosquitera-Pumarabule. 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 it is not expected influence from or to Mosquitera and Pumarabule. Toral mine is connected with another small mine, Aramil, located to its northwest.

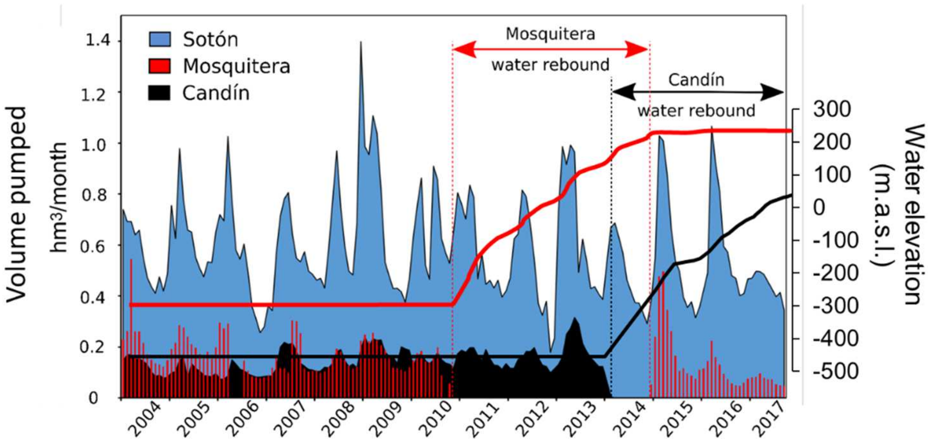
These mines are in a different closure stage. Candín is recovering the water level while Venturo is still with water level depressed as it was during the active phase.

Next Figure 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 is assumed, however, the very low permeability would mean very low water flow.



Monthly pumping values in Sotón (which pump water also from Venturo), Mosquitera and Candín are shown in the next Figure. Water rebound curves of Mosquitera and Candín are also shown. Sotón levels are still depressed. It can be seen how these stages are different.

When Mosquitera mine was flooded, Candín still was at the beginning of the recovery stage.

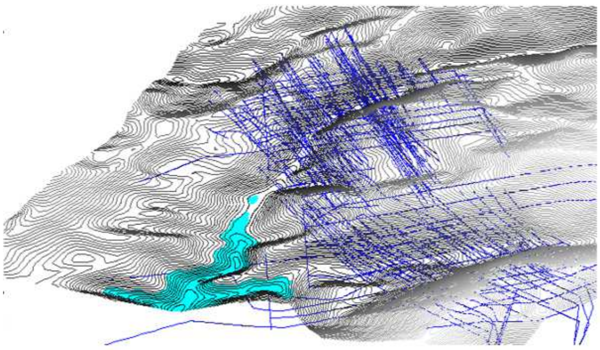


Risk assessment: Risk evaluation

Floods

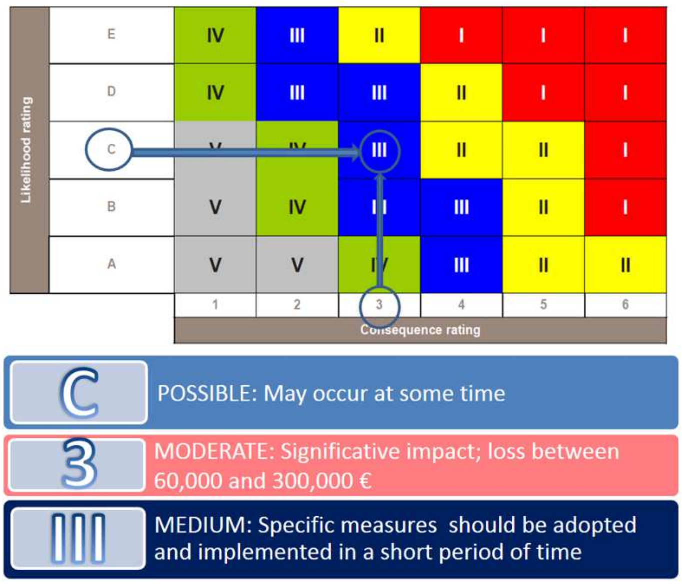
To evaluate the possible influence of water levels in the mine kept at an elevation of 235 m.a.s.l., the probability of occurrence of groundwater levels above selected surface elevations has been calculated.

Results of inundation risk was 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. The Candín River Valley is situated between 235 and 250 m.a.s.l. The area with the bigger probability is where the Candín river collects the waters from the Braña stream.



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.



Pollution of aquifers

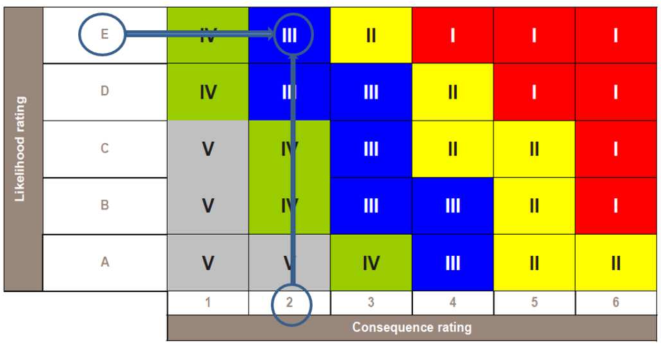
The possible mine influence on the different water points/aquifers is presented in the table below:

Code	Kind	UTM X	UTM Y	Level (mosl)	Mine influence	Observations	Recommendations
1305-3-0004	Spring	284912	4800163	240	NOT EXPECTED	Discharge from rain infiltrated water	In-situ analysis of basic hydrochemical parameters
1305-3-0009	Spring	285243	4800504	240	NOT EXPECTED	Discharge from rain infiltrated water	In-situ analysis of basic hydrochemical parameters
1305-3-0011	Pit with gallery	286071	4800796	200	YES	Elevation below security level. Possible flow from the mine.	Complete hydrochemical laboratory analysis and head monitoring
1304-7-0010	Drill	284861	4804906	280	NO from Mosquitera Pumarbaule	Out of the model domains. Possible influence of Aramil/Total system	Further evaluation in Aramil-Toral-Lieres area
1304-7-0026	Gallery	286552	4801441	260	POSSIBLE (from mountain mining)	Elevation above security head at Mosquitera-Pumarabule. Possible influence of mountain mines. No flooding expected while mantaining security 235 masl	Hydrochemical analysis and discharge estimates
1304-7-0027	Pit with gallery	286553	4801541	260	POSSIBLE (from mountain mining)	Elevation above security head at Mosquitera-Pumarabule. Possible influence of mountain mines. No flooding expected while mantaining security 235 masl	Hydrochemical analysis and discharge estimates
1304-7-0031	Spring	286675	4803324	265	NOT EXPECTED	Discharge from rain infiltrated water	In-situ analysis of basic hydrochemical parameters

The next Figure presents the risk analysis of the interaction with other aquifers.

Likelihood was rated with an "E", as the impact on the water point 1305-3-0011 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.



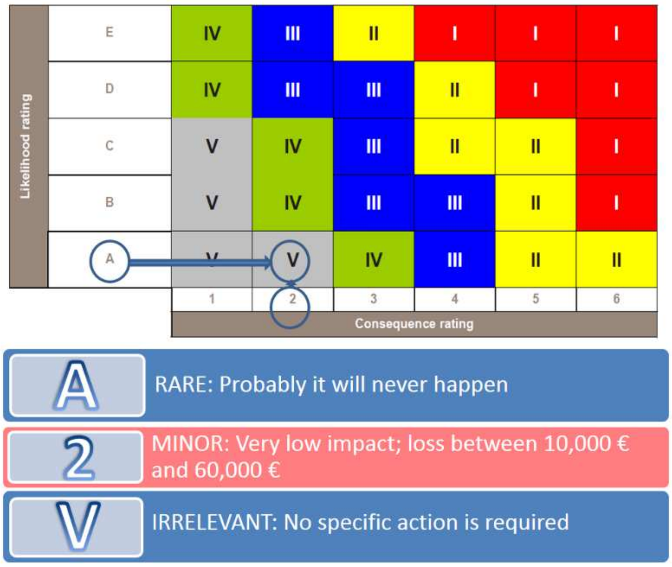
E — ALMOST CERTAIN: Will occur or could occur within weeks or months

2 — MINOR: Very low impact; loss between 10,000 € and 60,000 €

III — MEDIUM: Specific measures should be adopted and implemented in a short period of time

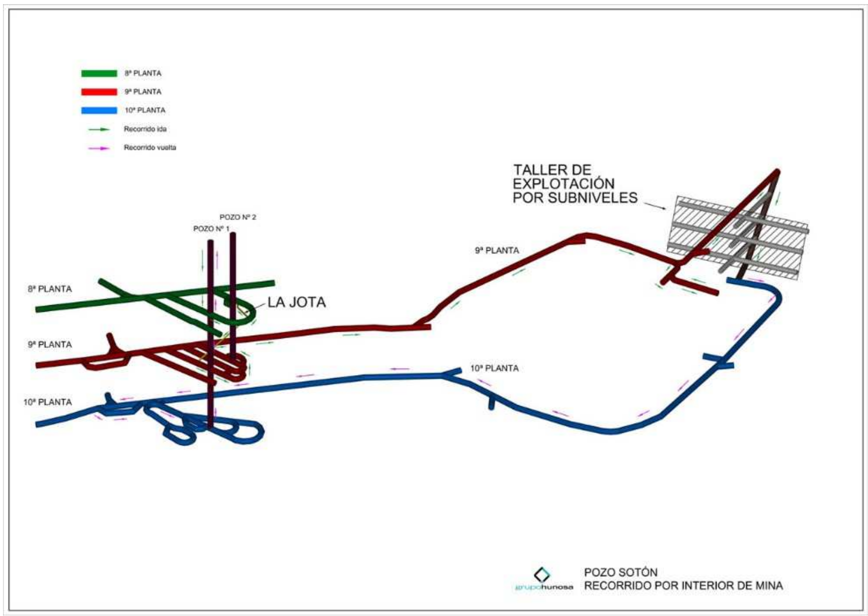
Flooding of other mines

The risk analysis of the interactions with other mines is presented below:



Likelihood was rated with an “A”, as it is very improbable that communications between isolated mines occur, and taking into account that the massif has very low permeability. On the other hand, the consequence rating was rated as “minor” or with 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.

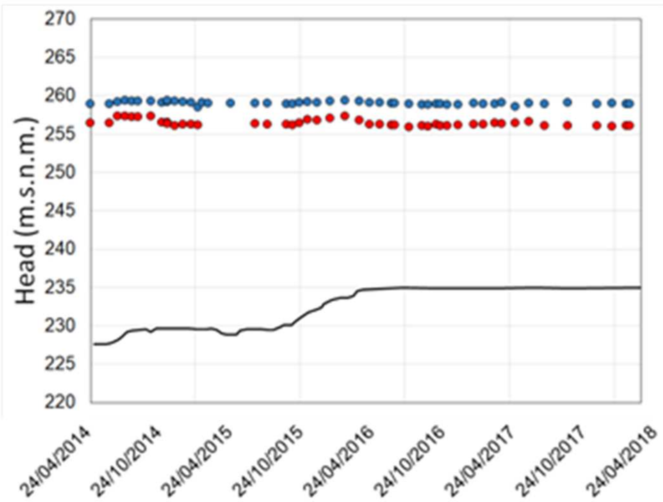
The consequence was not rated as “insignificant” because Sotón is the mine that Hunosa uses for touristic visits in its 8th, 9th and 10th floors and, in case that something happens, safety reasons will force to stop all the visit programs until the situation is completely under control:



Risk assessment: Proposed treatments

Floods

The proposed treatment method would be 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. daily better than monthly), as the estimation of recharge values are of extremely 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.

Pollution of aquifers

According to the risk analysis of pollution of underground aquifers, specific measures should be adopted and implemented in a short period.

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 the industry.

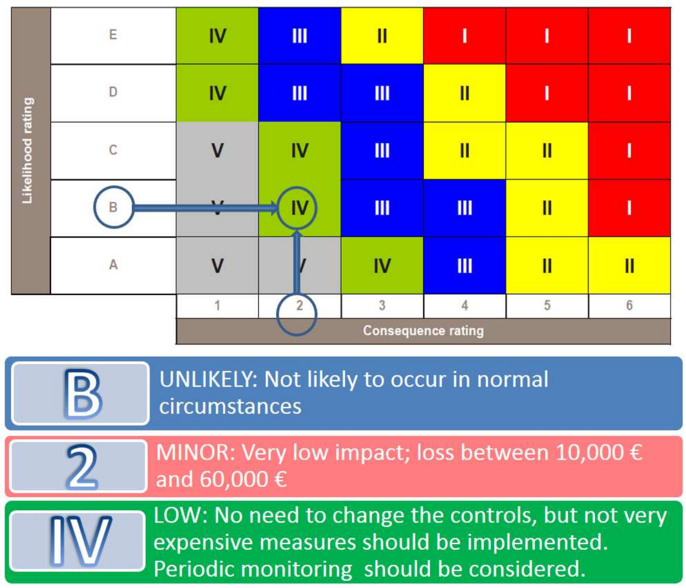
The periodicity of the controls or the possibility to stop them will depend on the characteristics of the water required by the industry, something that will have to be evaluated.

Risk assessment: Performance forecast

Floods

According to the proposed treatment, developing additional piezometric controls in the area that presents the higher risk of floods, that is, the south of Tuilla, near Mosquitera 2, would have the following effect on the risk of floods caused by groundwater:

- The likelihood rating will decrease from "C" to "B", that is, now the probability can be classified as unlikely: not likely to occur in normal circumstances.
- Simultaneously, the consequence rating will move from "3" to "2", that is, a minor or very low impact with a loss between 10,000 € and 60,000 € can be expected. Thus, the new scale of risk will be as follows:



The risk will be low after the piezometers are installed, with no need to change the controls, although not very expensive measures should be implemented. Three piezometers are recommended: one under the water level, the second over the water level and the third one within the Quaternary to detect influences from the river or from hanging or shallow aquifers.

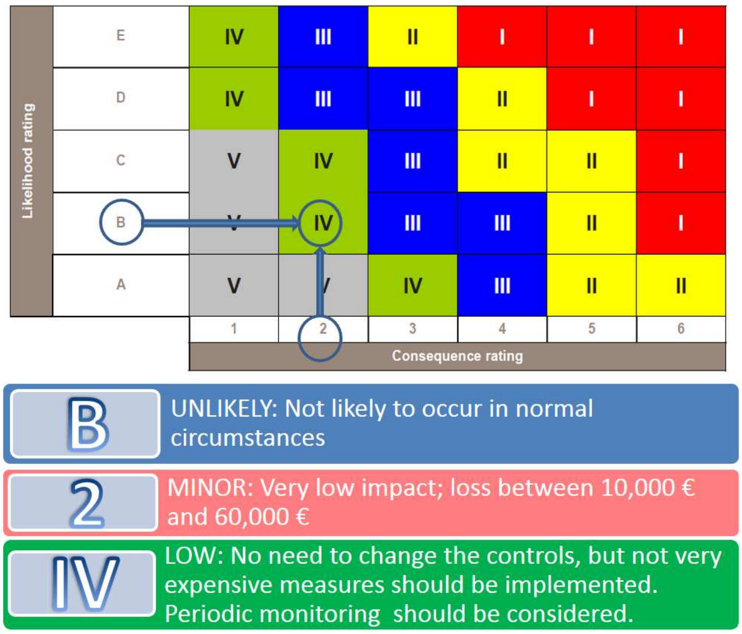
Installing independent powered water level alarm sensor in the piezometer over the water level, connected by phone with the person in charge, can represent a not very expensive measure implemented to keep the risk low. Naturally, periodic monitoring of the piezometers has to be considered, that has to be developed by the same people that control pumping and/or water quality parameters.

Finally, the installation of one weather station (which is relatively cheap) can provide data of rain and temperature on the study area, an advantageous information that could be linked to high-frequency series of pumping/levels in the mine, something interesting although not completely necessary.

Pollution of aquifers

The next Figure presents the risk analysis of the pollution of underground aquifers after introducing the proposed treatments.

The likelihood rating will be reduced from "E" to "B", as after implementing the controls the risk is not likely to occur in normal circumstances, while the consequence will remain minor.



Thus, there is no need to change controls but periodic monitoring has to be considered.

Economic evaluation: Cost evaluation

According to Deliverable 4.2, the likelihood for floods 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.

The first pollution treatment option will be 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.

The cost for the Installation of three piezometers near Mosquitera 2: one under the water level (approximately 40 m), the second over the water level (approximately 30 m) and the third one within the Quaternary (approximately 10 m) in order to detect influences from the river or from hanging or shallow aquifers, will be:

Piezometers installation = 80 m x 180 €/m = 14,400 €

The second treatment option will be 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. The Installation of an independent powered water level alarm sensor in the piezometer over the water level, connected by phone with the person in charge, will be:

Probe water level meter (30 m) = 400 €

3G SMS Control and Monitoring with solar panel = 1,000 €

Yearly line maintenance = 600 €

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 extremely importance to assess the infiltration to the aquifer and relate head variations with rain data.

Finally, 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. The installation of one weather station providing daily data of rain and temperature on the study area will cost:

Wireless weather station = 1,000 €

On the other hand, the periodic monitoring of the piezometers and the weather station will cost:

Yearly monitoring of piezometers and station = 2,400€

The risk will be low after the piezometers are installed, with no need to change the controls, although periodic monitoring should be implemented.

The likelihood of pollution of aquifers was rated with an "E", as the impact on the water point 1305-3-0011 it is quite clear to happen.

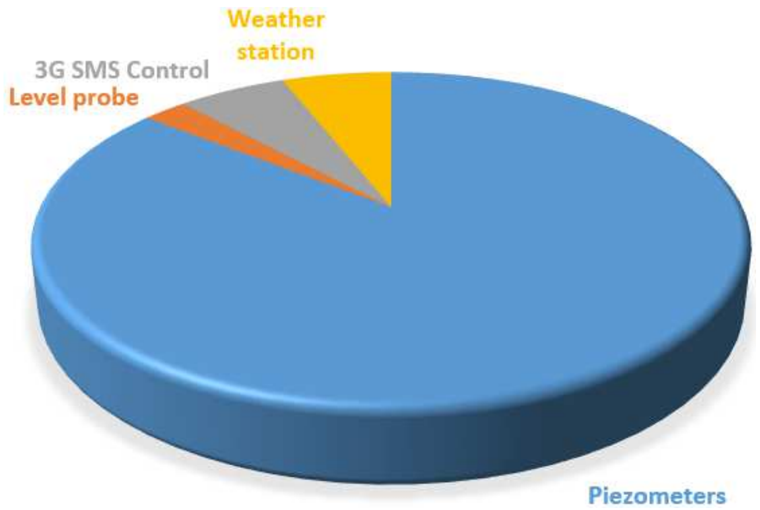
On the other hand, as the water from this water point is used for industrial purposes, the impact will be very low (monetary loss can be estimated between 10,000 € and 60,000 €), but specific measures should be adopted and implemented in a short period.

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. 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. We can establish a period of 5 years as long enough, according to the different models run with different initial concentration distribution.

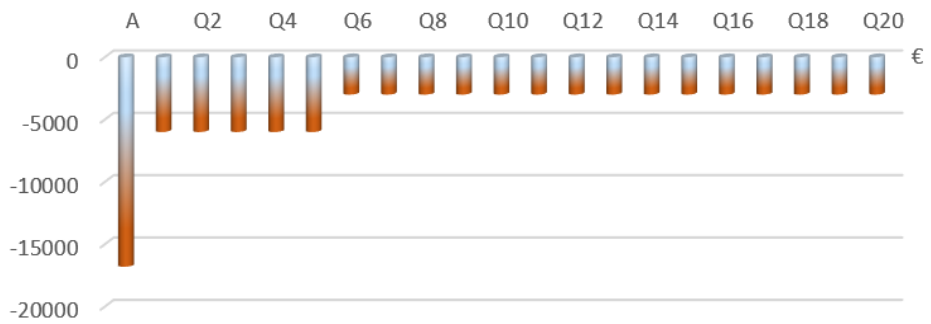
The cost for the water analysis during one year can be estimated in:

Yearly cost of water analysis = 250 € x 12 = 3,000 €

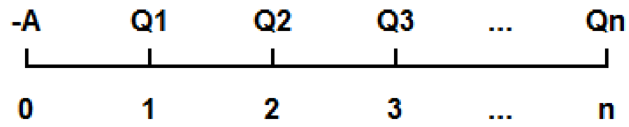
The next Figure represents the investments that have to be made at the beginning of the treatment period:



In the next Figure, the cash flows for the future 20 years are presented. After the fifth year, it should be possible to stop with the hydrochemical laboratory control analysis. That is the reason for the reduction of the cash flow from that year.



Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

Q1, Q2, Q3, Q4, Q5 = - 600 € - 2,400 € - 3,000 € = - 6,000 €

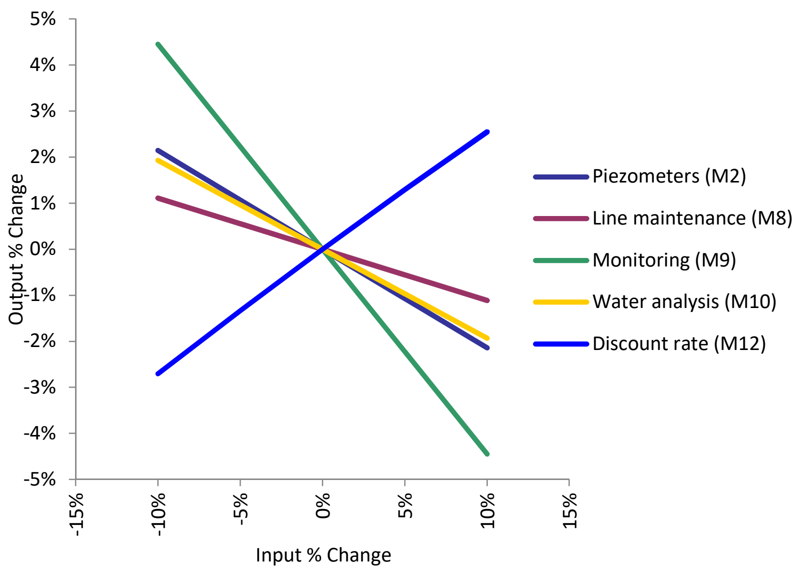
Q6 … Q20 = -600 € - 2,400 € = -3,000 €

k = 5%; n = 20

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 will be:

NPV = - 67,175 €

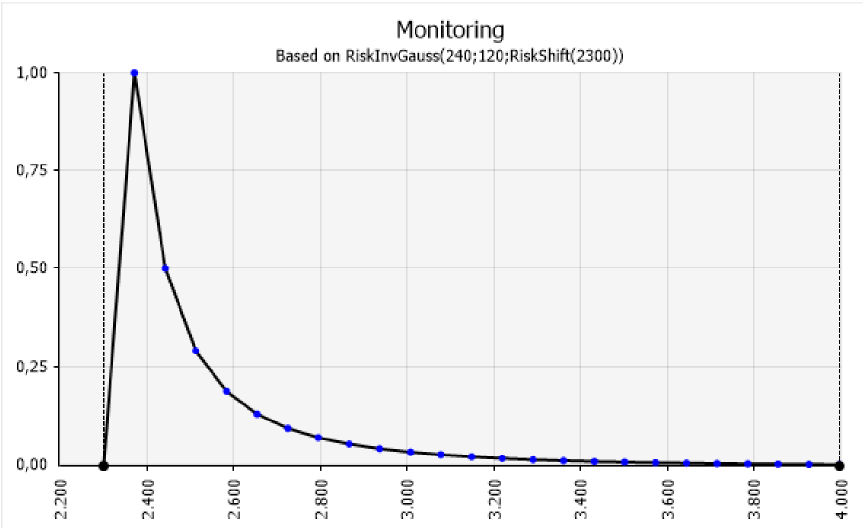
In order to estimate to which cost the MPV is more sensitive, a sensitive analysis was developed by means of allowing a ± 10% in every variable. The spider graph obtained was:



Economic evaluation: Uncertainty analysis

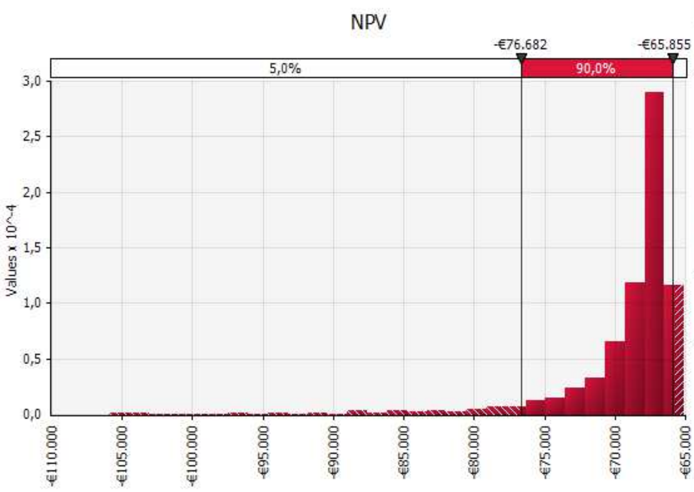
Thus, the two variables to which the NPV is more sensitive are the yearly cost of monitoring the piezometers and the station, the discount rate, and in third place the piezometers installation.

In order to undergo an uncertainty analysis, the yearly costs of monitoring the piezometers will be more rigorously modelled by an inverse Gaussian distribution centered in 2 300 € with parameters Mu = 240 and Lambda =120, in order to represent possible bigger prices but with a low probability:



On the other hand, no possible variations of the discount rate will be considered, but the piezometers installation will be modelled by a triangular function with parameters: (13,900, 14,400 and 15,400).

Running the Monte Carlo analysis, the NPV will be the following one:



	NPV
Cell	NPV!C1
Minimum	-€105.870,55
Maximum	-€65.067,50
Mean	-€68.909,72
90% CI	± €217,06
Mode	-€66.656,58
Median	-€67.553,38
Std Dev	€4.169,08
Skewness	-3,6129
Kurtosis	21,7116
Values	1000
Errors	0
Filtered	0
Left X	-€76.682
Left P	5,0%
Right X	-€65.855
Right P	95,0%
Dif. X	€10.827,22
Dif. P	90,0%
1%	-€87.759,65

So the NPV distribution obtained has a mean of -68,910 €, a minimum of -105,971 €, a maximum of -65,068 € and a standard deviation of 4,169 €.

Model: Conceptual model

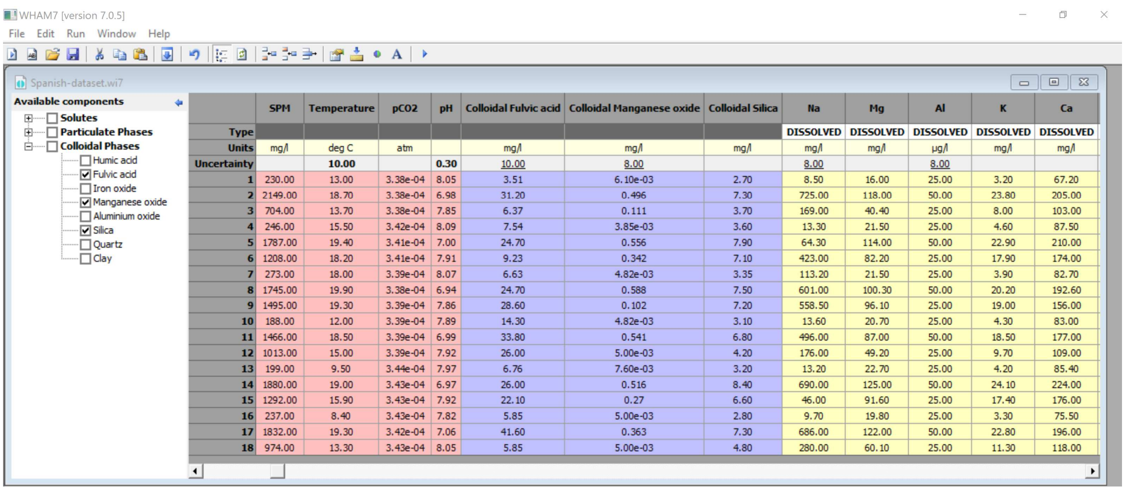
The Windermere Humic Aqueous Model (WHAM7) was used to model the discharged water quality (or surface water quality) at/around Mosquitera and Pumarabule Mines in Spain. WHAM7 is an equilibrium chemical speciation model that simulates the chemical reactions that occur when metals enter the water systems. 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 (Cl^-, SO_4^{2-}, 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.

In MERIDA, 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.

WHAM7 uses three types of data files: input files, which define the chemical composition of a system or systems; solute databases, which define the solutes that may be simulated, and the equilibrium constants and enthalpies of formation of solution complexes and precipitates; and phase databases, which include the parameters describing ion binding to the available binding phases. The input file is displayed in a spreadsheet-style format. Each row represents one chemical problem, with concentrations of solutes and colloidal/particulate phases to the input file.

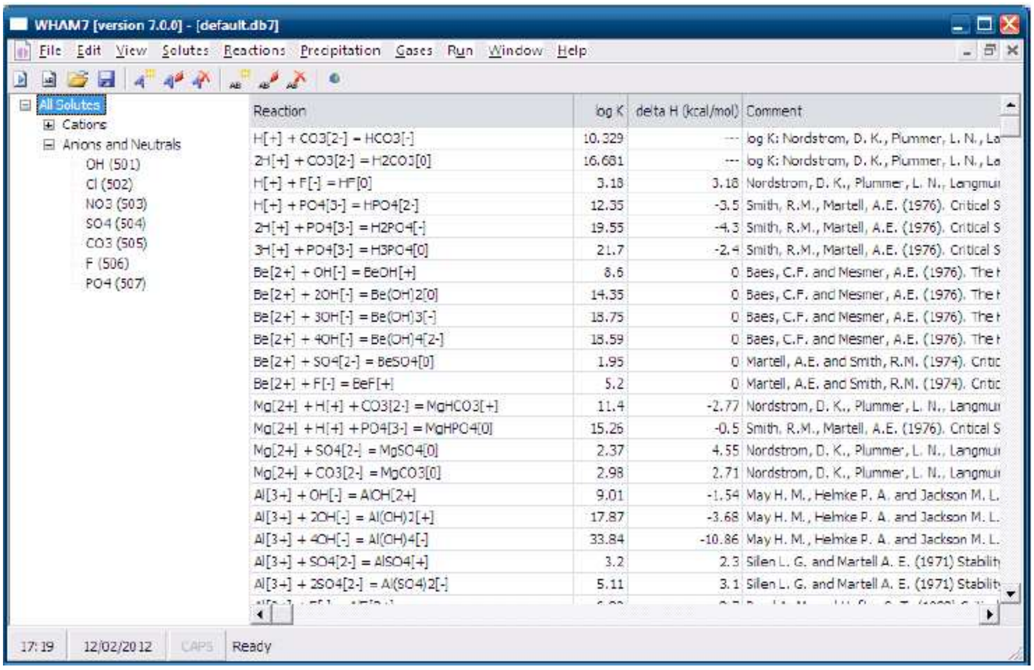


	SPM	Temperature	pCO2	pH	Colloidal Fulvic acid	Colloidal Manganese oxide	Colloidal Silica	Na	Mg	Al	K	Ca
Type								DISSOLVED	DISSOLVED	DISSOLVED	DISSOLVED	DISSOLVED
Units	mg/l	deg C	atm		mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mg/l	mg/l
Uncertainty		10.00		0.30	10.00	8.00		8.00		8.00		
1	230.00	13.00	3.38e-04	8.05	3.51	6.10e-03	2.70	8.50	16.00	25.00	3.20	67.20
2	2149.00	18.70	3.38e-04	6.98	31.20	0.496	7.30	725.00	118.00	50.00	23.80	205.00
3	704.00	13.70	3.38e-04	7.85	6.37	0.111	3.70	169.00	40.40	25.00	8.00	103.00
4	246.00	15.50	3.42e-04	8.09	7.54	3.85e-03	3.60	13.30	21.50	25.00	4.60	87.50
5	1787.00	19.40	3.41e-04	7.00	24.70	0.556	7.90	64.30	114.00	50.00	22.90	210.00
6	1208.00	18.20	3.41e-04	7.91	9.23	0.342	7.10	423.00	82.20	25.00	17.90	174.00
7	273.00	18.00	3.39e-04	8.07	6.63	4.82e-03	3.35	113.20	21.50	25.00	3.90	82.70
8	1745.00	19.90	3.38e-04	6.94	24.70	0.588	7.50	601.00	100.30	50.00	20.20	192.60
9	1495.00	19.30	3.39e-04	7.86	28.60	0.102	7.20	558.50	96.10	25.00	19.00	156.00
10	188.00	12.00	3.39e-04	7.89	14.30	4.82e-03	3.10	13.60	20.70	25.00	4.30	83.00
11	1466.00	18.50	3.39e-04	6.99	33.80	0.541	6.80	496.00	87.00	50.00	18.50	177.00
12	1013.00	15.00	3.39e-04	7.92	26.00	5.00e-03	4.20	176.00	49.20	25.00	9.70	109.00
13	199.00	9.50	3.44e-04	7.97	6.76	7.60e-03	3.20	13.20	22.70	25.00	4.20	85.40
14	1880.00	19.00	3.43e-04	6.97	26.00	0.516	8.40	690.00	125.00	50.00	24.10	224.00
15	1292.00	15.90	3.43e-04	7.92	22.10	0.27	6.60	46.00	91.60	25.00	17.40	176.00
16	237.00	8.40	3.43e-04	7.82	5.85	5.00e-03	2.80	9.70	19.80	25.00	3.30	75.50
17	1832.00	19.30	3.42e-04	7.06	41.60	0.363	7.30	686.00	122.00	50.00	22.80	196.00
18	974.00	13.30	3.43e-04	8.05	5.85	5.00e-03	4.80	280.00	60.10	25.00	11.30	118.00

Model: Numerical model

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

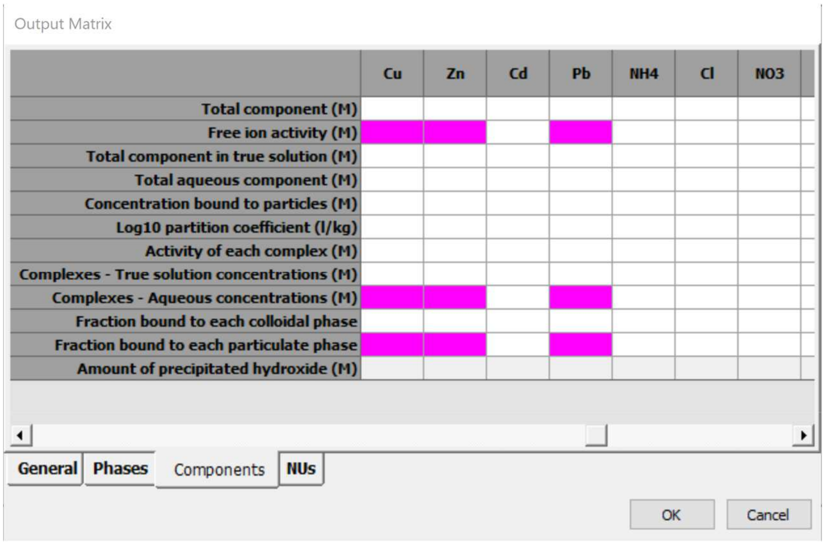
- As Dissolved Organic Carbon (DOC) is the most common parameter analysed in the laboratory, this needs to be converted to a reactive dissolved organic matter (DOM) fraction. The total DOM has been estimated to be two-times the DOC measured levels and that 65% of DOM behaves as an isolated active fraction. 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 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.



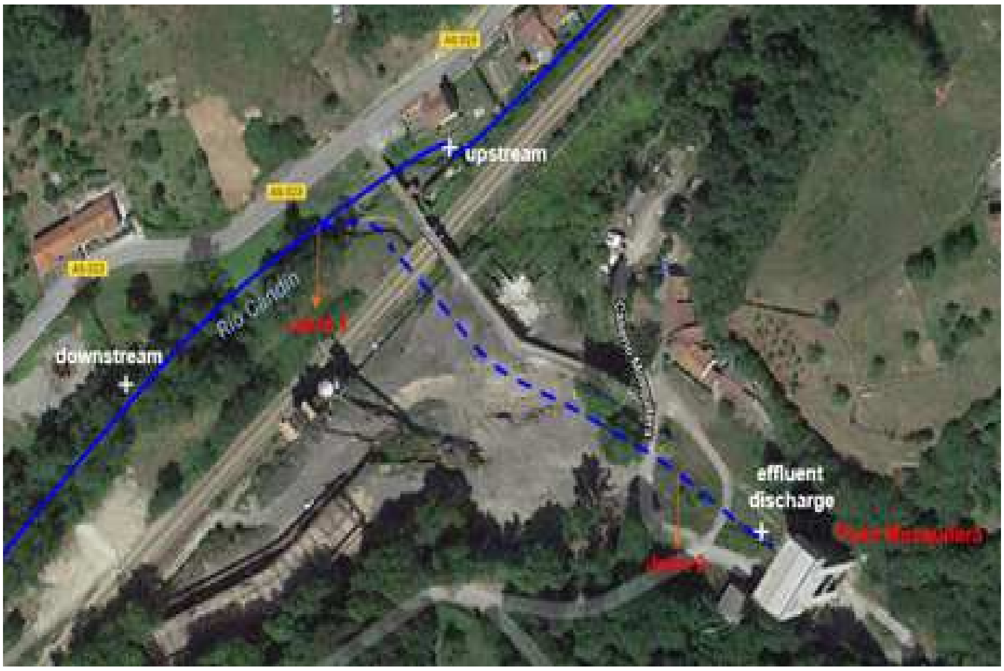
- Fe, Al and Mn have the tendency to oxidise, hydrolyse and/or precipitate in mine water environments. As pH levels for both mines were not low enough to prevent hydroxides from forming, all the iron and aluminium concentrations were assumed to precipitate as ferric and aluminium hydroxide, respectively; and manganese oxide (MnO_x) was considered the likely form for manganese.
- The precipitated iron hydroxide was also allowed to have a chemically active surface 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.

Model: Simulation results

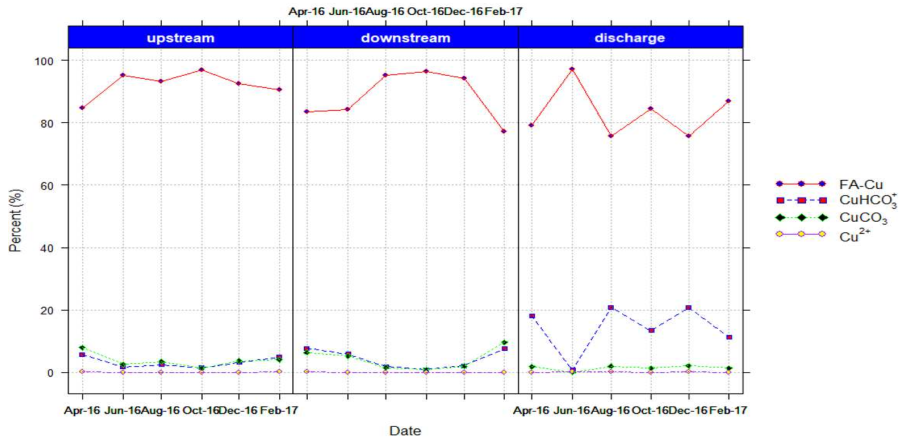
The output matrix of the model provides the component complex concentrations in the aqueous phase, the free ion activity and the fraction of each component for each of the colloidal phases.



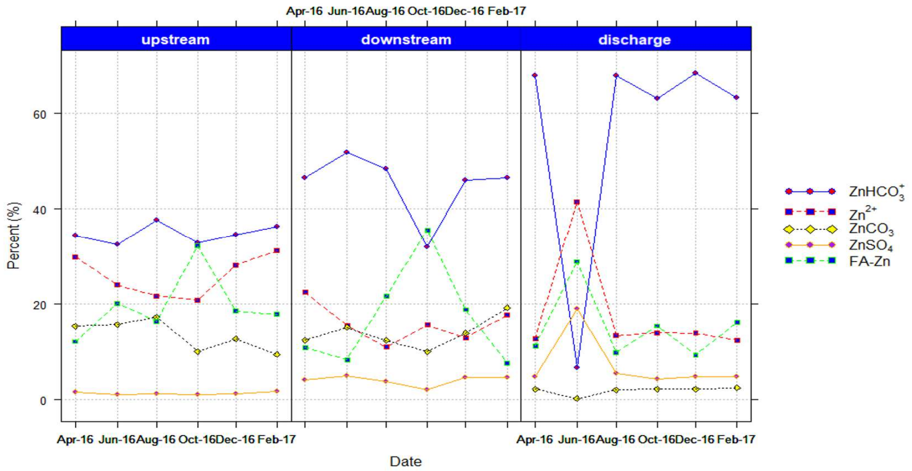
The results of the geochemical model provide the spatial/temporal species distribution for copper, zinc and lead. The water sampling locations at Mosquitera mine (Spain) are shown below.



Copper speciation in the surface waters of the Mosquitera mine region is 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 is also shown to bind with several inorganic ligands, notably carbonate and bicarbonate, but at a much weaker binding as compared to the organic matter.



WHAM modelling predicted that the zinc bicarbonate complex, $ZnHCO_3^+$, was the most predominant species, followed by the free ion Zn2+ and the Zn complex bound to organic matter (Zn-FA) for Mosquitera mine region surface waters. However, at lower alkalinity levels, the free Zn ion was the most predominant.



At Mosquitera mine region surface waters, 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.

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.

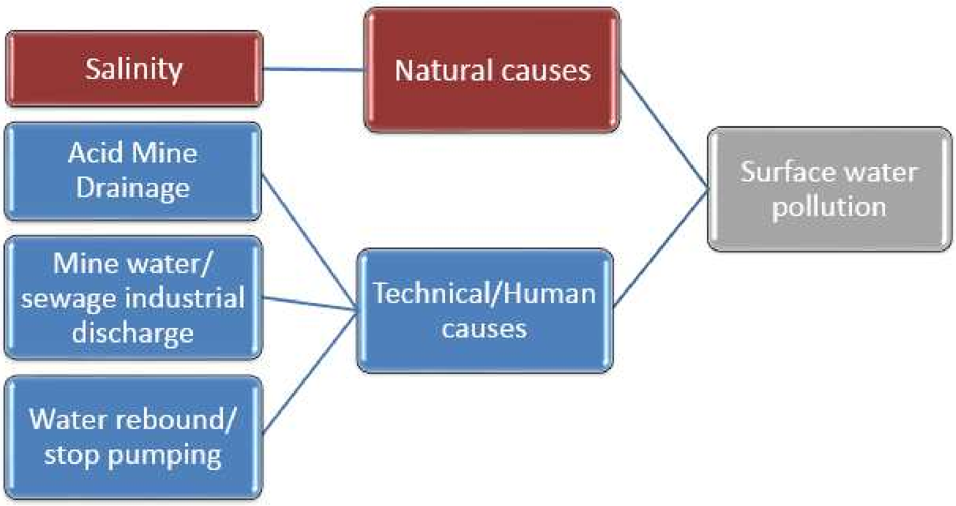
The geochemical speciation results for the free metal ions provided the necessary inputs for the bioavailability/ toxicity modelling used to perform the environmental risk assessment for surface waters around the abandoned coal mines studied.

Risk assessment: 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.

In the simplified "cause-and-effect" diagram shown here, illustrates the two main causal factors and the corresponding contributing factors that influence the level of risk associated with the surface water quality.



In addition to the above factors, interaction/ communication with other mines could also lead to pollution of local surface waters, if the discharge point of the acid mine water is located in the surroundings of such other mines.

When analyzing the surface water risk, associated sub-effects should also be considered in order to devise an efficient risk management plan.

According to the "source-pathway-receptor" elements concerning the risk posed by mine water, 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 assessment: Risk analysis

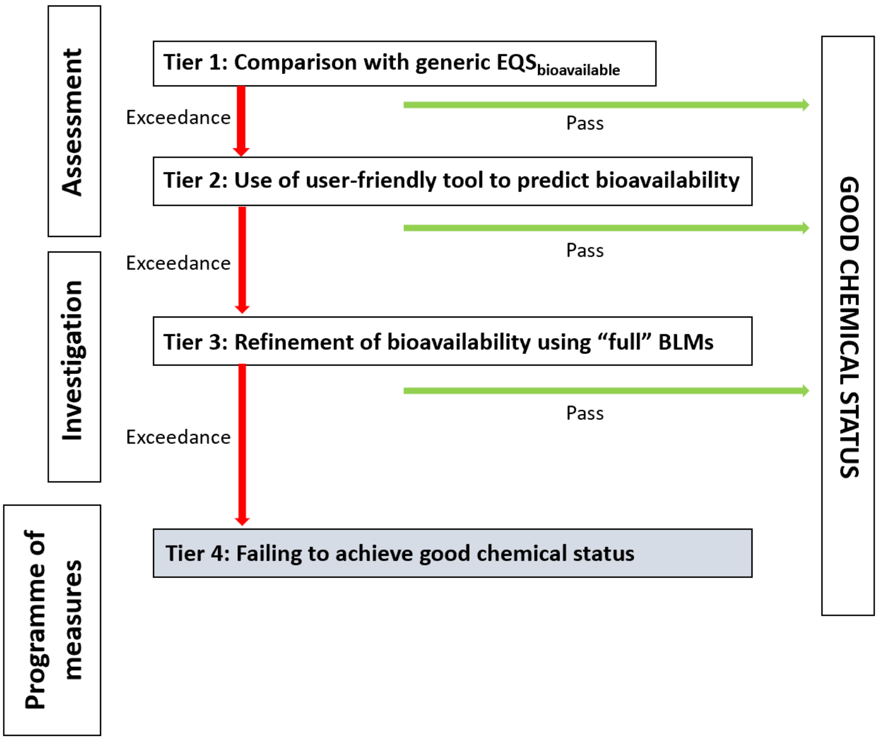
To assess the risk associated with surface water discharge, the bioavailable metal concentration was analysed including exposure and effect assessment steps. The assessment of exposure considers the concentration of the substances present in the environment. Subsequently, the effects assessment defines the extent that target organisms may be exposed to the contaminant.

The exposure assessment step 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). This is based on the analysed samples and measured discharge water composition.

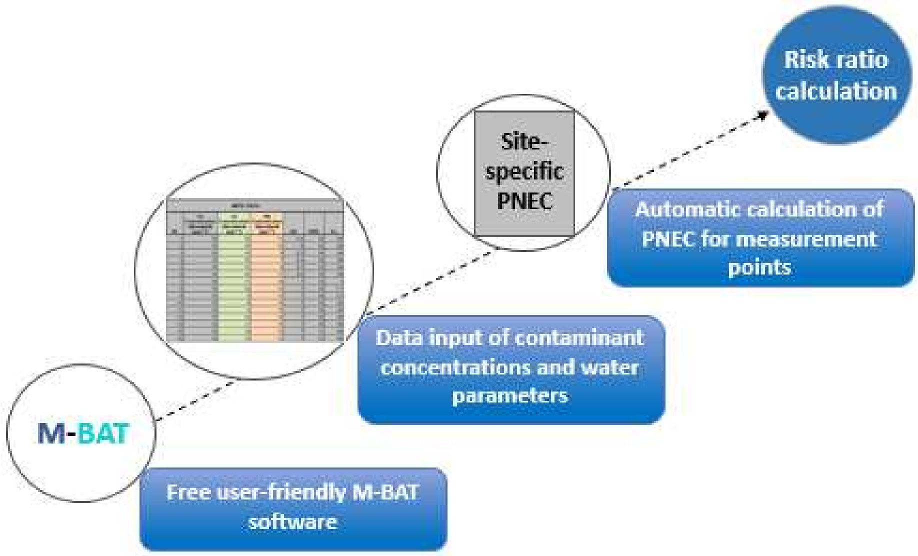
The effect assessment process is based on determining the ecotoxicological effects (NOEC) and is based on an appropriate method (probabilistic, algorithm, BLM), which allows the determination of the Predicted No Effect Concentration (PNEC). This value constitutes a protective concentration (a threshold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

User-friendly bioavailability tools approach: M-BAT for Cu, Zn, Pb and Mn

A flow diagram describing the possible stages of a tiered EQS compliance assessment for different metals (as a first step in the complete classic paradigm shown in the previous page) is shown below. These user-friendly screening tools mimic the BLM models and give an initial assessment of risks associated with metals in freshwater environments.



They require 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 approach to estimate a local PNEC and risk ratio is presented below.



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.

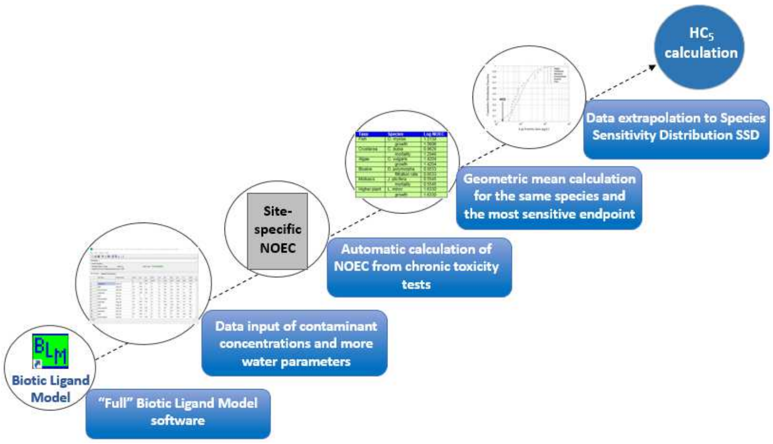
The analysed PNEC/bioavailable metal concentrations and corresponding risk ratio for the monitoring period studied are presented in the tables below.

INPUT DATA		RESULTS (Copper)			RESULTS (Zinc)			RESULTS (Mn)			RESULTS (Pb)		
Sampling location	Sampling Date	PNEC Copper (µg l⁻¹)	Bioavailable Copper (µg l⁻¹)	Risk Ratio	PNEC Zinc (µg l⁻¹)	Bioavailable Zinc (µg l⁻¹)	Risk Ratio	PNEC Manganese (µg l⁻¹)	Bioavailable Manganese (µg l⁻¹)	Risk Ratio	PNEC Lead (µg l⁻¹)	Bioavailable Lead (µg l⁻¹)	Risk Ratio
upstream	Apr-16	6.69	0.25	0.25	20.75	3.73	0.34	123.00	6.10	0.05	3.24	0.25	0.21
effluent	Apr-16	49.54	0.10	0.10	50.40	10.81	0.99	1581.62	38.57	0.31	24.00	0.25	0.21
downstream	Apr-16	17.68	0.15	0.15	28.32	6.08	0.56	293.53	46.51	0.38	5.88	0.44	0.37
upstream	Jun-16	16.80	0.10	0.10	32.01	2.42	0.22	184.45	2.57	0.02	6.96	0.12	0.10
effluent	Jun-16	50.98	0.10	0.10	49.16	11.09	1.02	1521.55	44.95	0.37	22.80	0.26	0.22
downstream	Jun-16	25.50	0.11	0.11	35.82	4.81	0.44	261.34	160.96	1.31	8.52	0.31	0.26
upstream	Aug-16	14.70	0.11	0.11	29.49	2.62	0.24	191.73	3.09	0.03	6.12	0.13	0.11
effluent	Aug-16	46.44	0.11	0.11	47.22	11.54	1.06	1708.96	42.34	0.34	22.80	0.26	0.22
downstream	Aug-16	26.63	0.10	0.10	81.05	2.12	0.19	287.90	43.62	0.35	24.00	0.11	0.09
upstream	Oct-16	35.18	0.05	0.05	49.91	1.55	0.14	271.66	2.18	0.02	13.20	0.06	0.05
effluent	Oct-16	50.27	0.10	0.10	50.75	10.74	0.99	1551.30	42.89	0.35	24.00	0.25	0.21
downstream	Oct-16	20.16	0.13	0.13	85.21	2.02	0.19	256.33	2.40	0.02	24.00	0.11	0.09
upstream	Dec-16	16.90	0.10	0.10	29.72	2.60	0.24	232.68	4.02	0.03	6.24	0.13	0.11
effluent	Dec-16	48.79	0.10	0.10	50.06	10.89	1.00	1612.54	39.36	0.32	24.00	0.25	0.21
downstream	Dec-16	20.16	0.13	0.13	71.06	2.42	0.22	256.33	129.56	1.05	20.40	0.13	0.11
upstream	Feb-17	16.33	0.10	0.10	26.63	2.91	0.27	311.08	1.98	0.02	5.40	0.15	0.13
effluent	Feb-17	54.84	0.09	0.09	53.18	10.25	0.94	1354.70	32.96	0.27	24.00	0.25	0.21
downstream	Feb-17	12.83	0.21	0.21	27.71	6.22	0.57	199.30	3.09	0.03	5.40	0.48	0.40

At Mosquitera mine (Spain) only the bioavailable metal concentrations for zinc and manganese in the waters of the mine region exceeded the EQS bioavailable (Zn:10.9µg/l and Mn:123µg/l) at the specific locations and given times (highlighted in red) indicating a potential risk for these metals. The rest of metals did not show any potential risk.

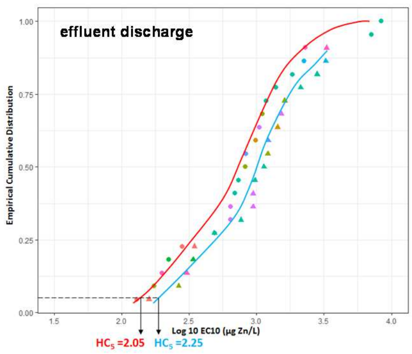
Probabilistic approach: Cu, Zn and Pb

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 Sensitivity Distribution function. The steps for the PNEC calculation based on the probabilistic approach are shown below.



Using the Species Sensitivity Distribution, the 5th percentile value is then specified (HC_5-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.

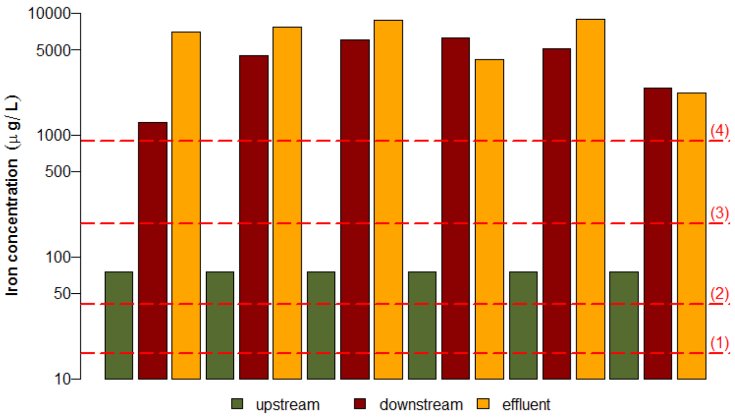
The Cu, Zn and Pb Species Sensitivity Distributions have been structured for the different sampling locations both mines. The zinc SSDs for effluent discharge at Mosquitera mine is presented below as an example.



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 in 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). Although the risk index for zinc at Mosquitera mine region was a bit higher than that of copper and lead, it was still low (less than 0.45) and unlikely to cause any adverse effect.

PNEC/EQS comparison approach: Fe, Cl and SO_4

As iron is also an important source of mine water pollution, it has been considered in the risk analysis. The hydrochemical data from the impacted locations at the Mosquitera mine region show a significant increase in iron concentrations, ranging from 75 to 8,905 µg/l. Elevated levels were mainly found downstream and in the effluent from the mine discharge, indicating that pyrite weathering is an important chemical process present in the Candin stream. Iron concentrations for the Mosquitera mine region at the different sample locations are shown below. Fixed PNEC thresholds have been established based on chronic and acute ecotoxicity databases and different derivation approaches to represent the toxicity of iron (shown as red horizontal dashed lines in bar plot below).



1. PNEC long-term: 16mg/l (TGD deterministic approach based on 3 species)
2. PNEC short-term: 41mg/l (TGD deterministic approach)
3. PNEC long-term: 186mg/l (MANAGER probabilistic approach from SSDs)
4. PNEC short-term: 887mg/l (MANAGER probabilistic approach from SSDs)

Based on the risk ratio, PEC/PNEC, iron toxicity can have a significant impact on aquatic ecosystem for the Mosquitera mine, for both downstream and effluent discharges from the mine. High levels of chlorides can also make it difficult to achieve good or moderate ecological status in rivers. At Mosquitera mine region, downstream discharges failed the PNEC long-term; while effluent discharges failed also the drinking criteria in the majority of the samples.

1. PNEC long-term: 139µg/l (MANAGER probabilistic approach from SSDs)
2. Drinking standard: 250µg/l (WHO and US.EPA Ambient Quality Criteria)
3. PNEC short-term: 644µg/l (MANAGER probabilistic approach from SSDs)

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.

4. PNEC long-term: 115µg/l (TGD deterministic approach based on 3 species)
5. Drinking standard: 250µg/l (WHO and US.EPA Ambient Quality Criteria)
6. PNEC short-term: 303µg/l (MANAGER probabilistic approach from SSDs)

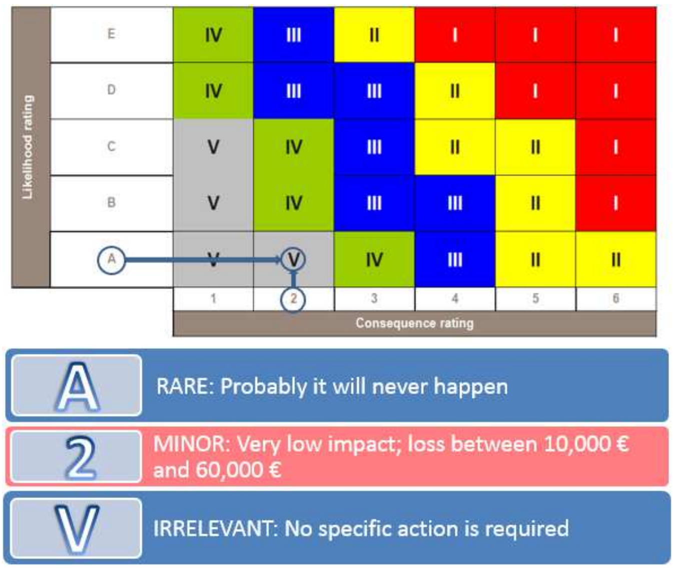
At Mosquitera mine region, both downstream and effluent discharges failed the PNEC long-term; while effluent discharges failed the drinking criteria in the majority of the samples.

Risk assessment: Risk evaluation

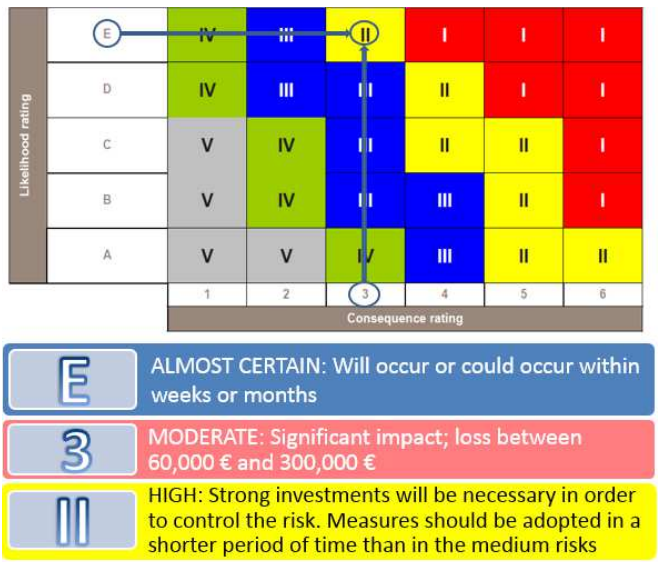
The chemical and aquatic toxicity risk analysis results were used to produce a risk index for each particular contaminant.

For Mosquitera mine 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 mine region.

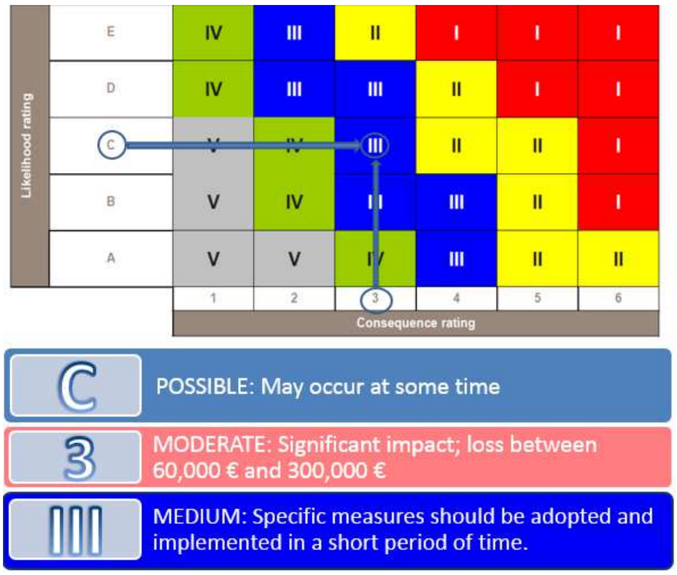
A risk matrix was also prepared for manganese for Mosquitera mine region surface waters. The same matrix applies for the zinc concentrations at effluent discharge. Similarly, no specific action is required.



Although there is no potential risk associated with heavy metals, there is risk associated with iron concentrations.

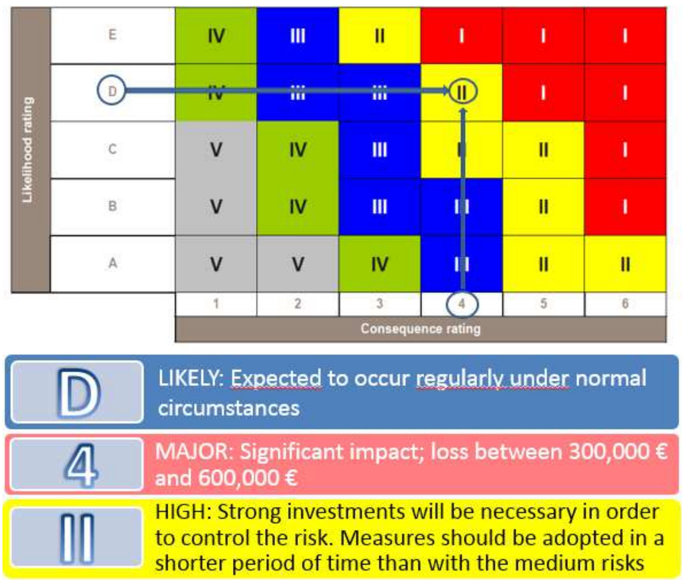


Additionally, the risk for chlorides for effluent discharge at Mosquitera mine region is medium and some additional measures need to be considered.



On the other hand, the risk for downstream discharge at Mosquitera mine region is low and there could be a minor loss between 10,000 and 60,000€.

Finally, the sulphates risk matrix for the downstream and effluent discharge samples at the Mosquitera mine region is presented below.



Risk assessment: Proposed treatments

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

It is necessary to take steps to monitor regularly the concentrations of these substances in the surface water following mine closure.

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 is considered a better approach for net alkaline waters. It is the simplest type of passive treatment and is used to treat mildly acidic or net alkaline waters containing elevated Fe concentrations.

Its primary function 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.

A typical aerobic wetland system is a shallow, surface flow wetland vegetated with aquatic plants such as cattails. They translocate O_2 to the subsurface through their roots, which aids metal oxidation; but also help to prevent channelization of the waters flowing through the wetland, slowing water velocities and aiding solid-phase metal removal via sedimentation.

The AMD flows horizontally through the ponds and over substrate and the oxidation reactions precipitate the oxides and hydroxides. The depression that holds the wetland may or may not be lined with a synthetic or clay barrier.

Depending on landscape conditions, the lining can be intended to either to keep treatment waters from draining out through the depression's base or to prevent environmental waters from moving into the system and thus diluting the waters to be treated.

Aerobic wetlands have been shown to be an efficient and cost-effective remediation method, and have been used in 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

The Cost Effective Sulphates Removal (CESR) process removes high concentrations of sulphates through addition of hydrated lime ($Ca(OH)_2$), which precipitates calcium sulphates.

The CESR process essentially consists of four steps:

1. Initial precipitation of sulphate as gypsum
2. Precipitation of metals as hydroxides in a gypsum matrix
3. Additional sulphate removal via ettringite precipitation
4. pH reduction using re-carbonation.

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).

Capital and operating costs will depend upon the flow rate, the sulphates concentration to be removed, the final sulphates concentration to be achieved, and other water quality parameters (e.g., sodium and chloride concentrations).

Operating costs are typically 1.14 € to 2.28 € per 1,000 l treated for removal of sulphates, based on reagent consumption. For example, the reagent cost would be approximately 1.14 € per 1,000 l 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

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.

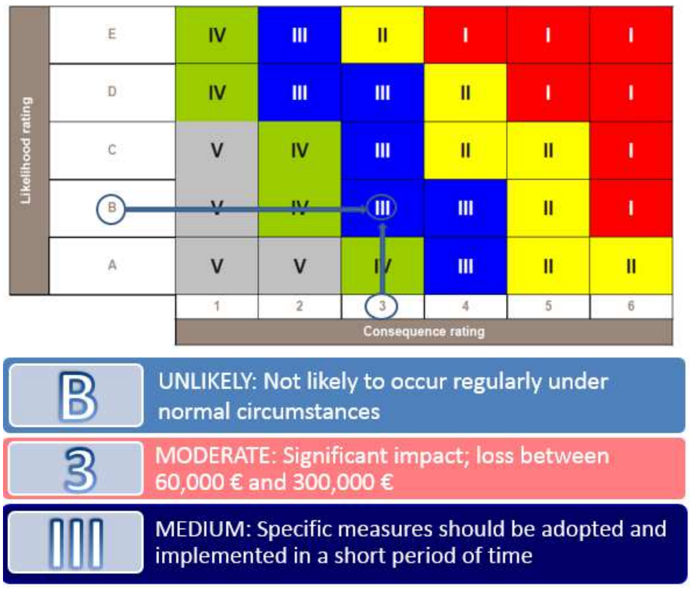
As the effluent does not need to be heated at high temperatures, as the water boils at 35-40°C when working under vacuum, the energy requirements are lower.

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 l/h, with a typical operating cost of 2.4-4.8 € per 1,000 liters of condensate.

Risk assessment: Performance forecast

The different treatment options, as introduced, will aim to minimise the risks and the probability of any adverse effect associated with the chemical parameters. Hence, both the likelihood and the consequences ranking will be reduced. Solutions, especially for iron, need to target to lower the likelihood ranking from “E” to “B” and therefore the consequences to be reduced from “4” to “3”.



Regular monitoring, especially of the contaminants having a high level of risk, needs to be considered, whether water treatment has to be continued.

Economic evaluation: Cost evaluation

According to Deliverable 4.2, there is no risk associated with copper, lead or manganese, and thus, no specific actions are required.

The likelihood associated with iron concentrations was rated with an "E", as iron concentrations are expected to occur almost certainly. The impact in this case will be moderate (monetary loss can be estimated between 60,000 € and 300,000 €), and thus the risk will be high, with strong investments necessary in order to control it. Measures should be adopted in a shorter period than the medium risks.

In this case, the 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. It is the simplest type of passive treatment and is used to treat mildly acidic or net alkaline waters containing elevated Fe concentrations.

Its primary function 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.

We will select the cheapest method, the aerobic wetland. Taken into consideration that the terrain to be used belongs to the mining company, the cost can be estimated in:

Aerobic wetlands = 55,000 €

A small maintenance of the area during the five years that according to the calculations is expected to be needed, can be estimated in:

Yearly wetlands maintenance = 600 € x 12 = 7,200 €

Additionally, the risk for sulphates discharge at Mosquitera mine region is high and strong investments will be necessary in order to control the risk. Measures should be adopted in a shorter period than with the medium risks. Likelihood was rated with a "D" as the risk is expected to occur regularly under normal circumstances, and the impact will be major, with significant impact and losses between 300,000 and 600,000 €.

In order to treat the risk associated with sulphates, 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, has been selected. 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 between 0.73 € to 1.5 € per 1,000 liters treated for removal of 1,500 mg/l of sulphates, based on reagent consumption.

Thus, the portion of the operating cost is also directly related to the sulphates concentration that needs to be removed. In Mosquitera-Pumarabule case, the concentration of sulphates at the effluent discharge is around 670-950 mg/l, and downstream concentration is around 200-750 mg/l.

The investment needed in order to treat an annual amount of water of 2,500,000 m3, according to the studies done, will be:

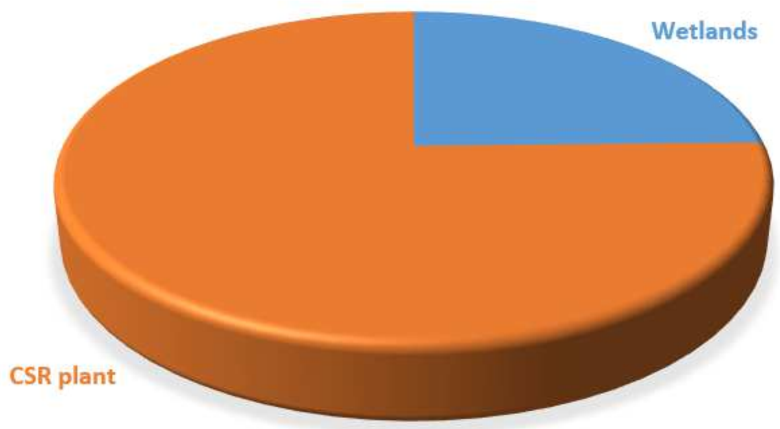
CESR plant = 168,000 €

Taking into consideration that it should be needed to remove less than 250 mg/l, so the operating costs can be estimated in 0.18 € per 1,000 l, so the annual operating cost will be:

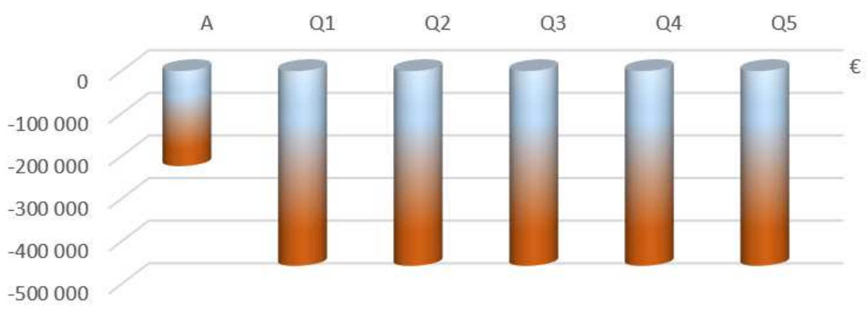
Yearly operating cost = 2.5 x 106 x 0.18 = 450,000 €

It has to be considered that this process will be necessary only during the first five years after the end of the flooding of the mines.

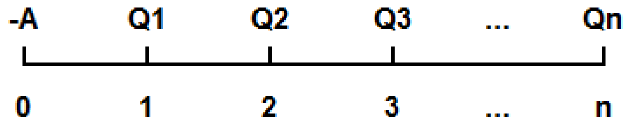
The next Figure represents the investments that have to be made at the beginning of the treatment period:



In the next Figure, the cash flows for the future 5 years are presented. After the fifth year, it should be possible to stop with the treatments, according to the findings during the project.



Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

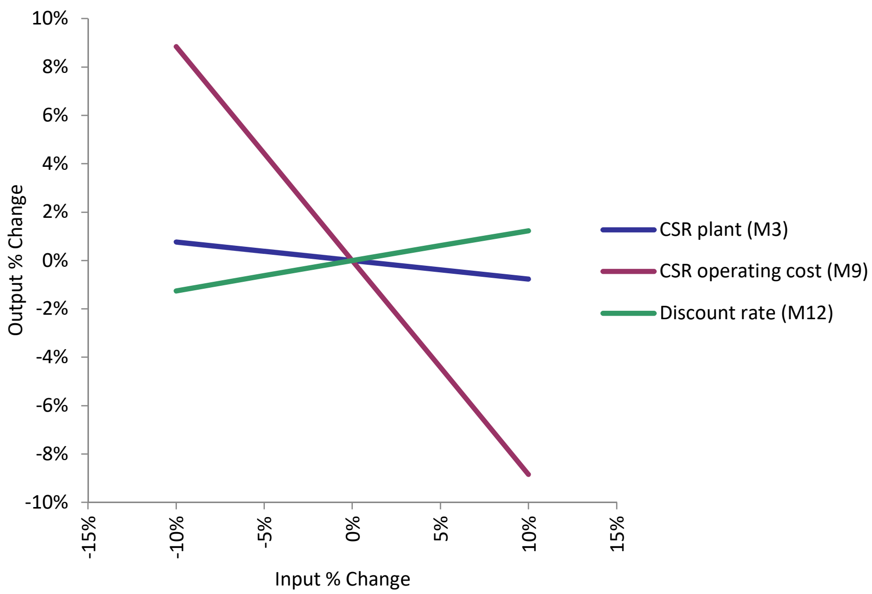
Q1, Q2, Q3, Q4, Q5 = -7,200 € - 450,000 € = -457,200 €

k = 5%; n = 5

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 will be:

NPV = - 2,202,437 €

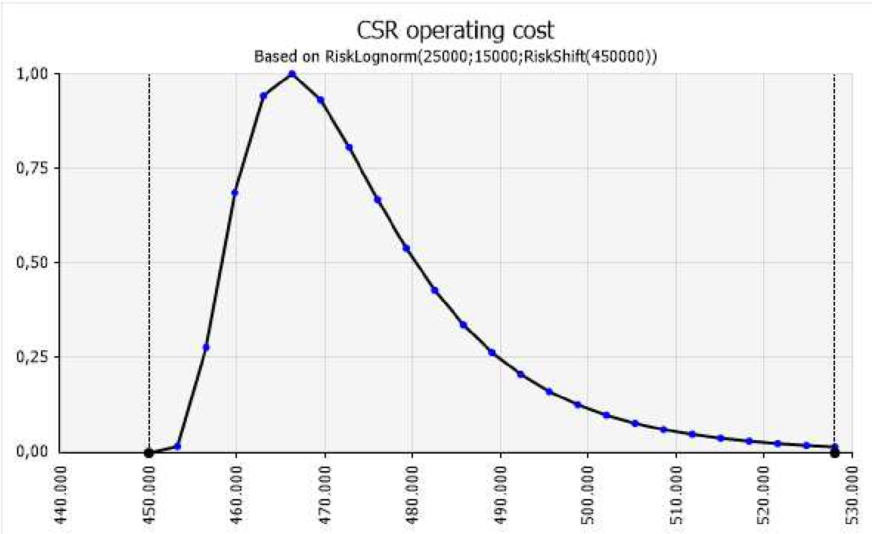
In order to estimate to which cost the MPV is more sensitive, a sensitive analysis was developed by means of allowing a ± 10% in every variable. The spider graph obtained was the following one:



Economic evaluation: Uncertainty analysis

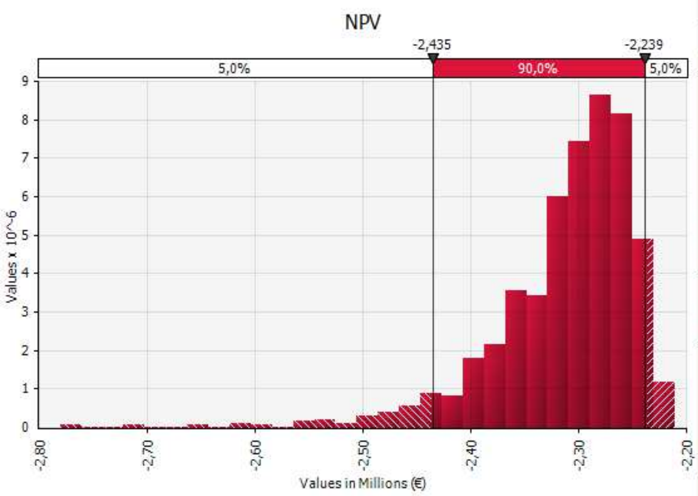
In this case, it was quite clear which the result will be. The main variable in this analysis are the CESR operating costs, while the investment needed in the CESR plant as well as in the aerobic wetlands are almost irrelevant for the purposes of the sensitivity analysis.

In order to undergo an uncertainty analysis, we will model the yearly costs of the CESR operating costs by means of a Lognormal function, as it is one of the function that better models natural phenomena like the amount of rain in this case. This distribution will be centered in 475,000 and with a standard deviation of approximately 15,000. μ value will be 25,000 and σ value 15,000.



On the other hand, no possible variations of the discount rate will be considered, but the investments will be modelled by triangular functions with parameters varying a 10% up and down.

Running the Monte Carlo analysis, the NPV will be the following one:

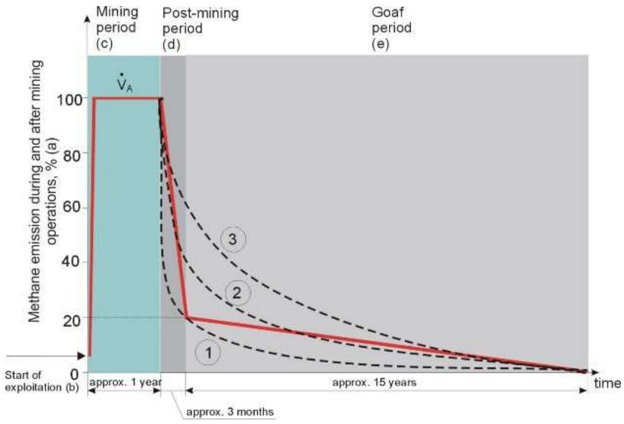


	NPV
Cell	NPV!C1
Minimum	-€2.780.485,49
Maximum	-€2.210.636,94
Mean	-€2.310.645,91
90% CI	± €3.396,90
Mode	-€2.256.521,79
Median	-€2.294.842,66
Std Dev	€65.245,94
Skewness	-1,8878
Kurtosis	9,3154
Values	1000
Errors	0
Filtered	0
Left X	-€2.435.034,91
Left P	5,0%
Right X	-€2.238.691,85
Right P	95,0%
Dif. X	€196.343,06
Dif. P	90,0%
1%	-€2.541.491,25

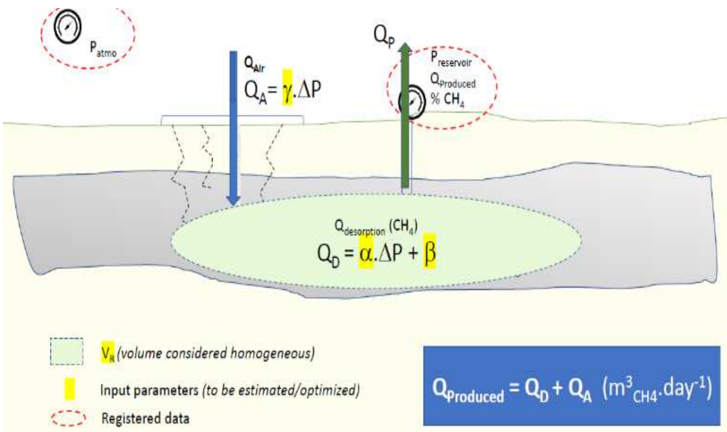
So the NPV distribution obtained has a mean of -2,310,646 €, a minimum of -2,780,485 €, a maximum of -2,210,637 and a standard deviation of 65,246 €.

Model: Conceptual model

As the main assumption, the model must include 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.



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.



The key parameter is a volume of emitted methane, which can be assessed following the model of methane emission from panel goafs after finishing mining operations. In order to assess the amount of methane that is released from goafs a following formula is being used:

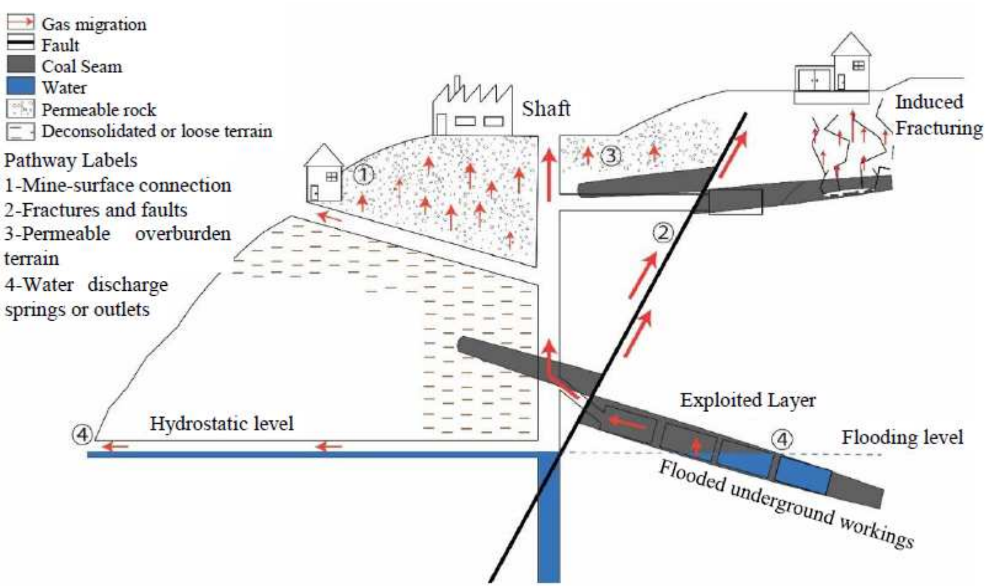
For Spain (where coal seams are subvertical – highly inclined):

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

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 CH4/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.

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.



Source: UNECE, (2019)

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 Cα 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.

Model: Numerical model

It is expected that the numerical model will contain elements representing voids, such as liquidated galleries, shafts and goafs. The model also contains elements that affect the analyzed phenomenon, such as flooded coal seams and mine areas. Connections between mine areas and shafts allow water and gas to flow. These elements represent important gas migration paths to the surface layers and areas of mines bordering the abandoned mine.

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 with a closed mine. For this purpose it is recommended to use a special software to model gas flow in the mine. Mine ventilation network simulators like Ventgaph software have been sucessfully used for mining operations. Based on one dimensional airflow approximation they provide a simple, easy to interpret representation of ventilation systems. Within the frames of MERIDA project this functionality has been extended to the period of abandonemet. At first the evolution of the emission of methane from goafs to the voids of a closed mine within sufficiently long period is to be foreseen. 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.

For extended and complicated systems of workings characterized by domination of length over the dimension of cross-section (shafts, galleries), a one-dimensional modeling is still feasible. Equations conforming to Kirchhoff's first and second laws were also developed. Pressure losses are proportional to the mass stream for the filtration Darcy flow and for turbulent the losses are proportional to the square of the mass flow. Hence, in general, the equations are non-linear and their solution is obtained by iteration methods.

Radon

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.

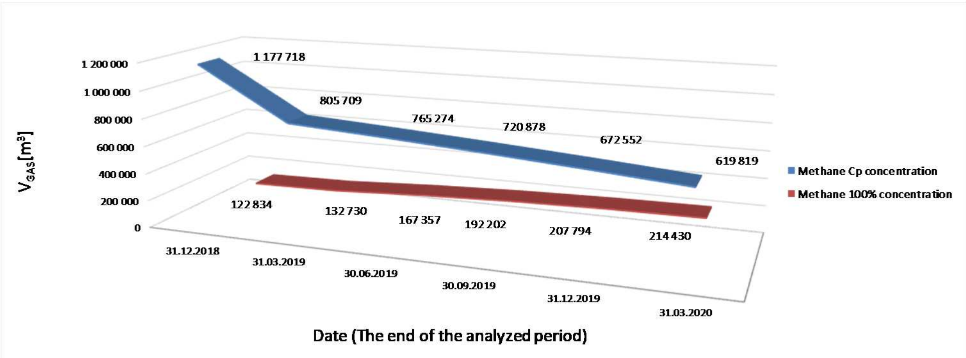
Supplementing this software by modules modelling radon exhalation, its radioactive decay and the losses during transport in the ventilation system of a mine provides a tool which may be used to predict the radiation hazard in underground mines.

Model: Simulation results

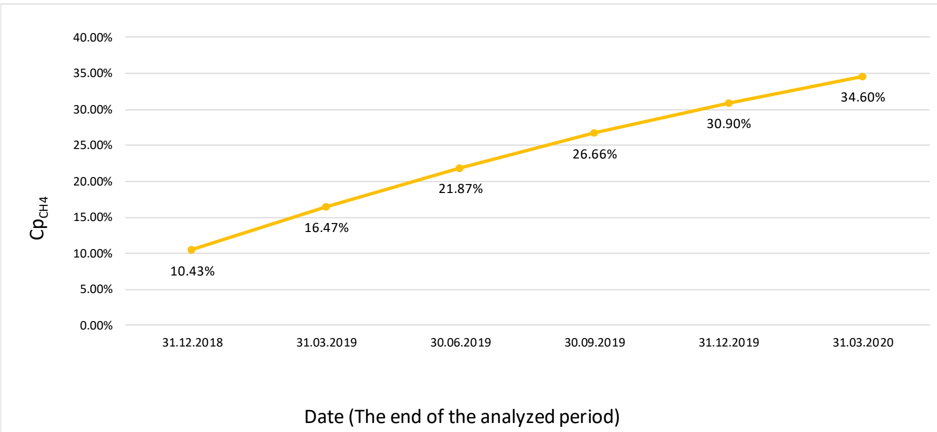
The original purpose of those simulators was the flow in galleries and shafts, but may be extended to any flow path characterized by a flow rate. This concept has been used in the model of filtration flow in goafs applied in the VentGoaf module of the Ventgraph simulator. Initially the description did not consider the composition of the mine air, just the flow rate. Knowing the flow rates and the composition at the branch/path inlet one may solve equations of advection transport of admixed gases. Supplementing this description with gas sources and dependencies for mixing streams of gases in junctions leads to gas transport models, which make the Mine Ventilation Network Simulators useful for the analyses of migration of mine gases to the atmosphere. Another result of MERIDA was a development and implementation of the Ventgraph Radon module modelling radon exhalation, its radioactive decay and the losses during transport in the ventilation system of a mine. This software is a tool for prediction the radiation hazard in underground mines and at points of release of this gas to the atmosphere.

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.

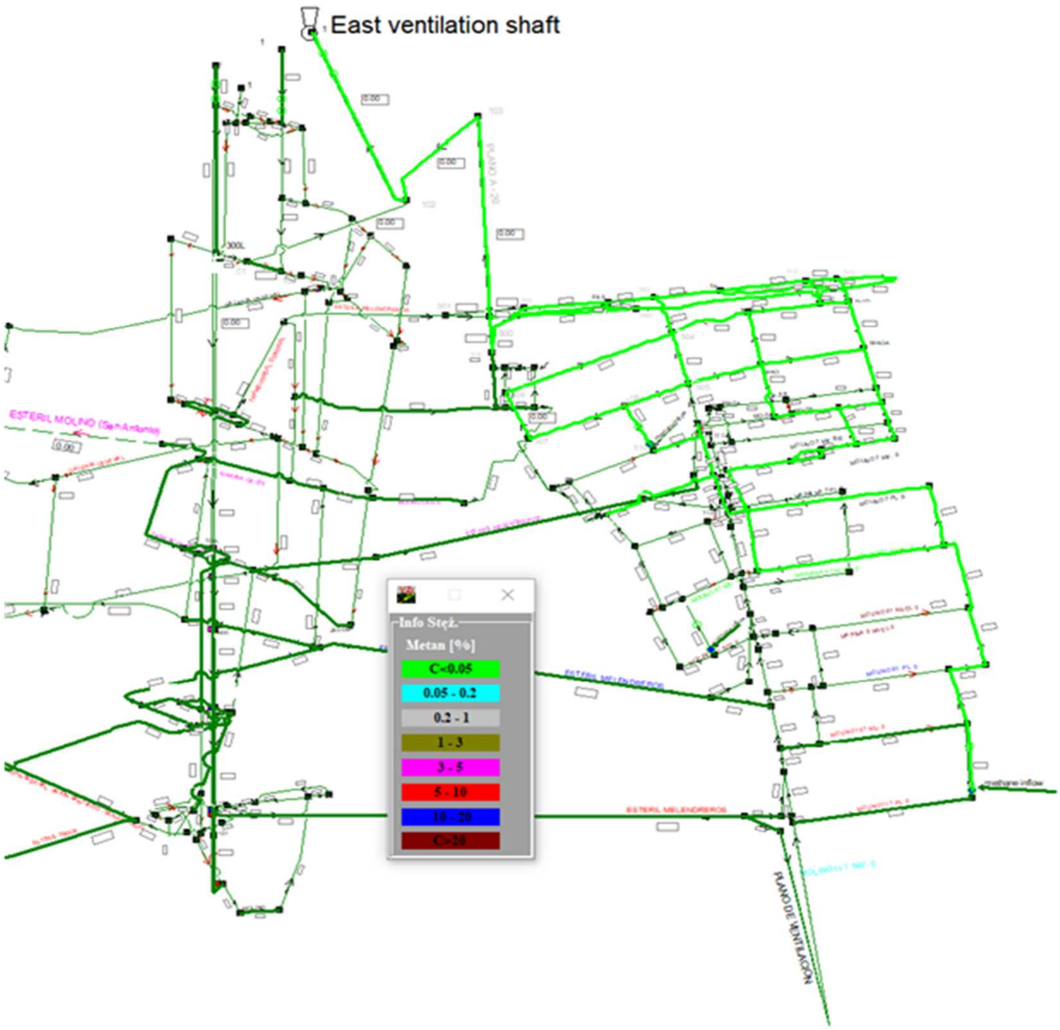
Secondly, comparing the calculated volume of gas evolved with the volume of voids allows for the assessment of the potential gas hazard.



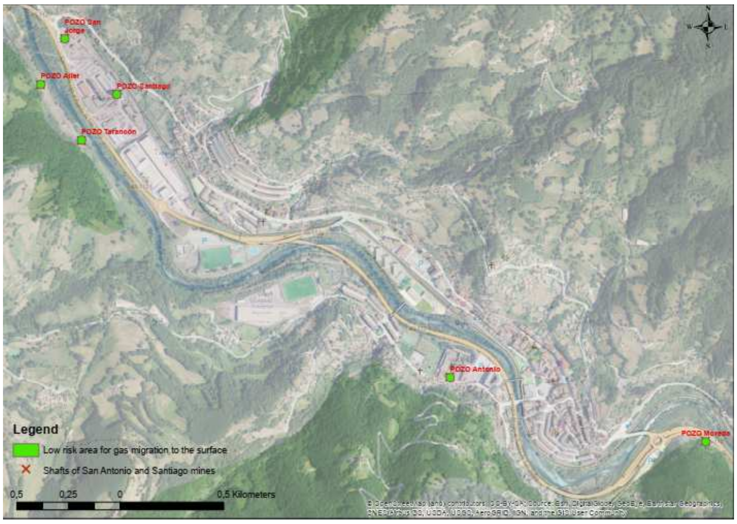
Finally, methane concentrations for individual periods of time in the mine voids treated as a reservoir are calculated.



After full identification of the parameters indicated above and analysis of the data correctness, the Ventgraph software can be used. It should start from getting or building a calibrated model of the ventilation system just prior to the beginning of abandonement. Then a set of simulations of gas migration from underground sources through non flooded system of voids towards atmosphere may be performed. For a given abandonement plan the effects of stepwise sealing of mining levels and regions followed with stoppage of ventilation and capping the shaft outlets and further process of flooding of the system of undeground voids can be modelled and subjected to a multi-varant analyses. 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 of the simulation for eastern ventilation shaft in Santiago mine (2033) are presented below.



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 floding 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:



Radon

The calculated distributions of radon concentration is presented below 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 (Calpha), as calculated with the use of the VentGraph-Plus-module Radon programme.

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.

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).

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.

Member States shall establish a national action plan addressing long-term risks for radon exposures in dwellings (article 103.1). Prone areas can 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. In Asturias only soil gas concentration was measured.

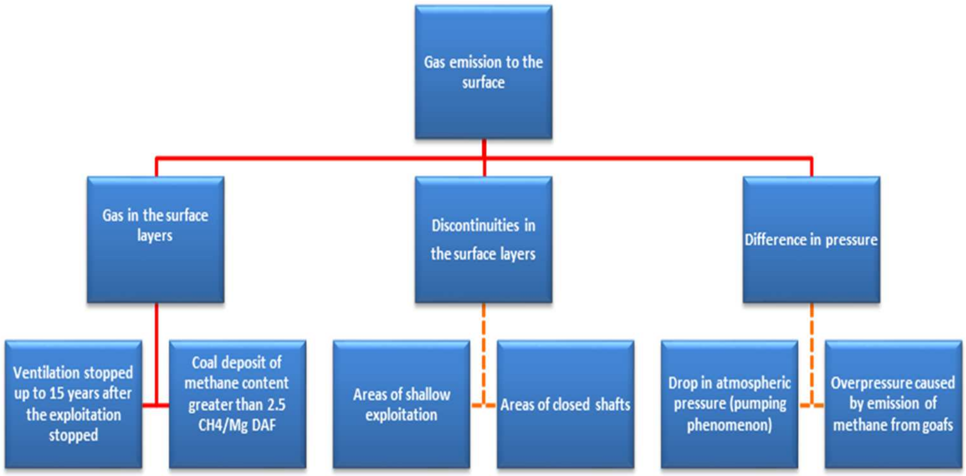
In most countries the uniform method for assessing the risk of radon penetrating from the underlying soil or bedrock, based on determining the radon index of the building site, proposed by Czech scientists, was implemented. Radon long-term monitoring, with use of nuclear track detectors is the appropriate technique to monitor the hazard in dwellings and workplaces.

Risk assessment: Risk identification (methane)

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.

Hence, in a simplified way, the diagram below presents the dependence in form of branches of the fault tree with logic gates: “OR” (orange dashed line) and “END” (red solid lines).

The fault tree method is applied to analyse the risk of occurrence of unfavorable events (disasters, accidents, failures) as well as to analyse the course and circumstances of the events that have already occurred.



The dependences seen in the tree are the basic criterion determining whether to conduct further analysis – if none of the elements linked with red lines occur, there is no need to analyse the risk associated with the migration of gases to the surface.

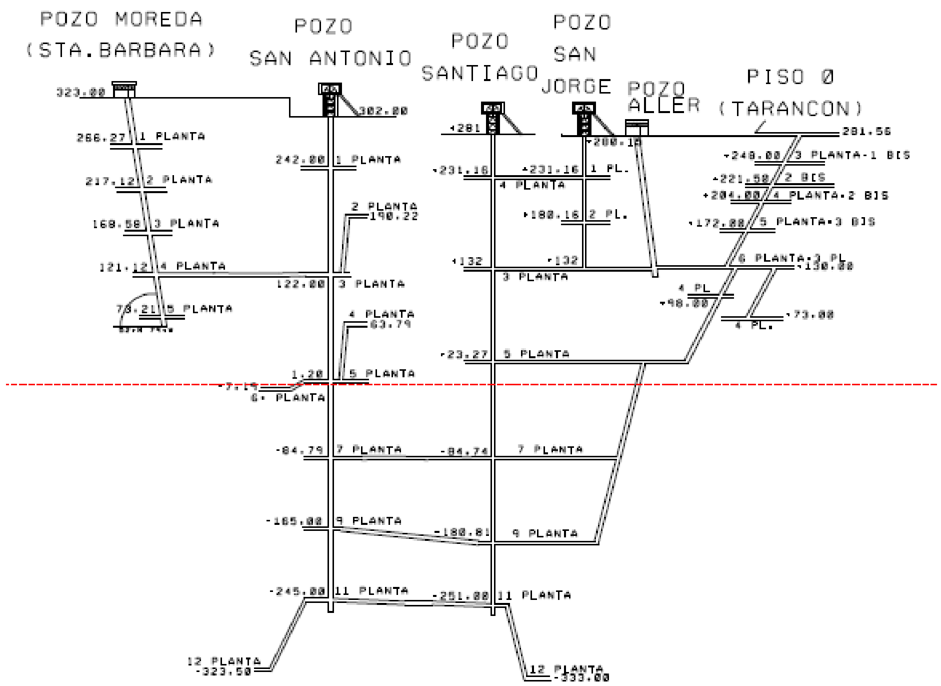
If all the conditions linked with red lines occur, it is necessary to conduct an analysis following the cause-and-effect model based on standard IEC/ISO 31010, 2009 that was adopted within the MERIDA project.

The model of data analysis presented in the project was adapted to the conditions of two Spanish mines: San Antonio and Santiago. San Antonio mine was closed at the beginning of 2004 while in Santiago mine the closure process has not finished yet, as there was no data available for Mosquitera and Pumarabule mines.

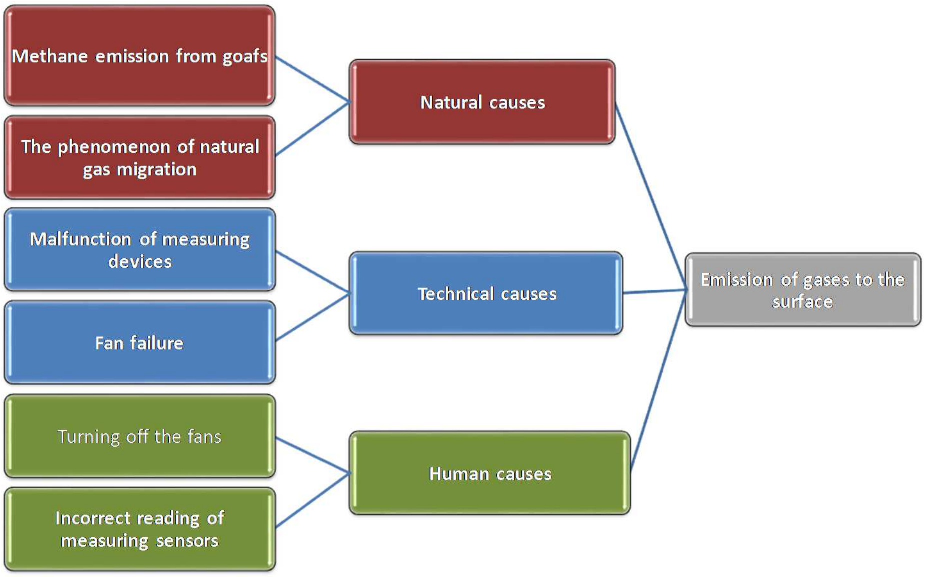
During the analyses and design works, the mines were connected through an operating ventilation network: the main fans of the system and two ventilation shafts and three downcast shafts. Therefore, within the framework of the conducted risk assessment, the amount of methane emitted from goafs and the places of its possible migration to the surface were taken into consideration.

Due to the fact that the mines have one operating ventilation network connected to the surface they were not treated as a reservoir.

There is no risk of gas migration to other mines, as the Moreda inclined pit (1945-circa 1990) is closed and sealed, San Jorge (1939-1995) has the head of the pit sealed and its galleries are coincident with the ones from Pozo Santiago, and Aller and Tarancón are included in the ventilation network.



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 factors influencing the risk of gas migration to the surface are presented below.



Risk assessment: Risk identification (radon)

The most important factors influencing radon concentration in a rock body are the contents of uranium and radium in the mined layers and in the overburden.

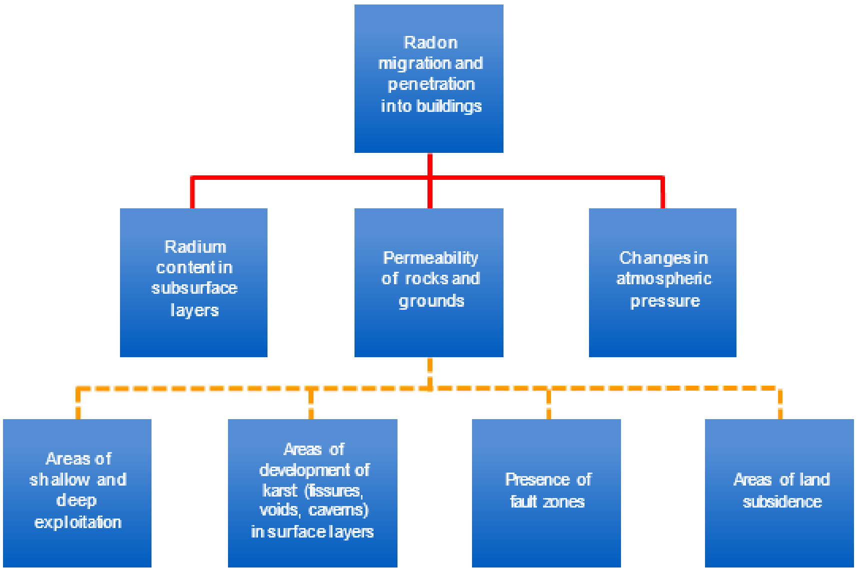
The process of radon transport is controlled by the permeability of the ground, thus any cavity that exists under the overburden has the potential to accumulate elevated radon concentrations. Another group of factors producing changes in the physical properties of rocks, which enable radon migration, are mining-induced effects such as the formation of voids, depressions, and subsidence of the surface, or rejuvenation of fault zones. The numerous cracks and fissures associated with faults constitute preferential pathways for gas migration. Changes in the concentration of radon in the air entrapped in the soil allow the path of faults to be tracked.

The mining practice confirms that mining exploitation rejuvenates fault zones, which are the source of mining tremors. The stress state of the rock mass, altered because of mining exploitation, can cause the loosening and disintegration of rocks. This is the reason for the release and migration not only of methane but probably also of radon. According to the literature, the local zone of rock weakening along the fault in some cases it can reach up to several meters on both sides.

Due to rock disintegration, the surface and volume from which radon exhales, and migrates can be significant. Moreover, the transport of gases through a newly created pathway to the surface is easier than through an undisturbed structure.

German scientists had observed that significantly higher concentrations of radon in the soil are measured in a relatively narrow zone, the boundary of which overlaps with that of the area of subsidence of the surface above the exploitation area.

The diagram below presents the dependence in form of branches of the fault tree with logic gates: “OR” (orange dashed line) and “AND” (red solid lines).



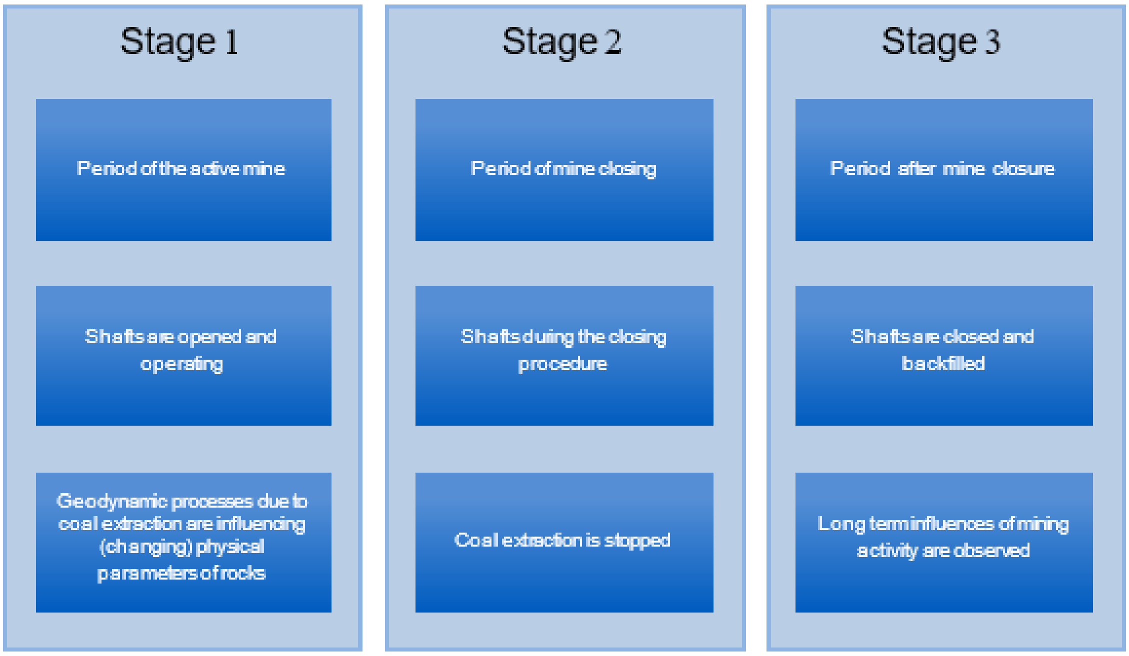
The areas where radon emission to the surface and its penetration into buildings can occur are: the sites where mining operations were conducted close to the surface, the areas affected by faults, areas of settlement and the areas of closed shafts.

It is generally considered that the sites of the disintegration of the surface layers, due to the above factors 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.

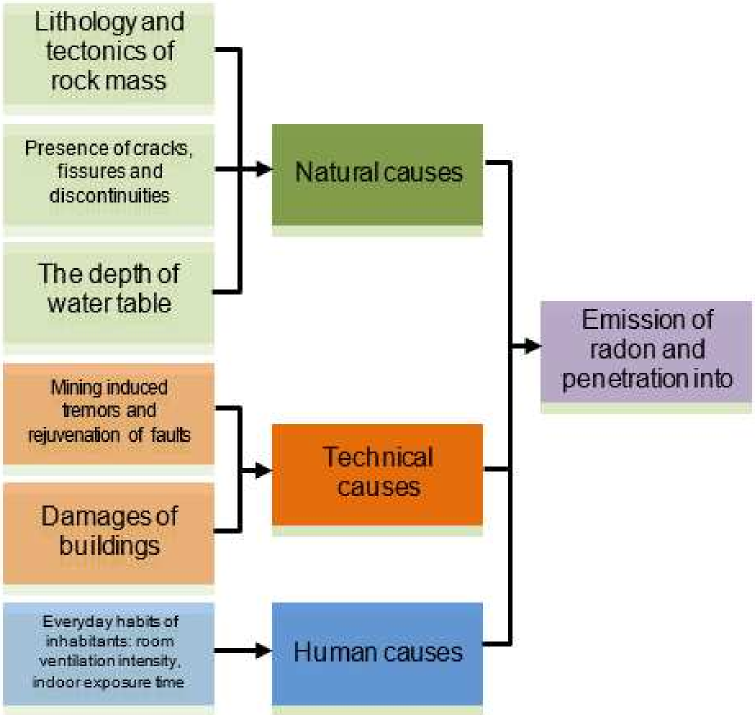
The phenomenon of radon migration and penetration into building in mining and post-mining areas could be presented in three stages:



Stage 1

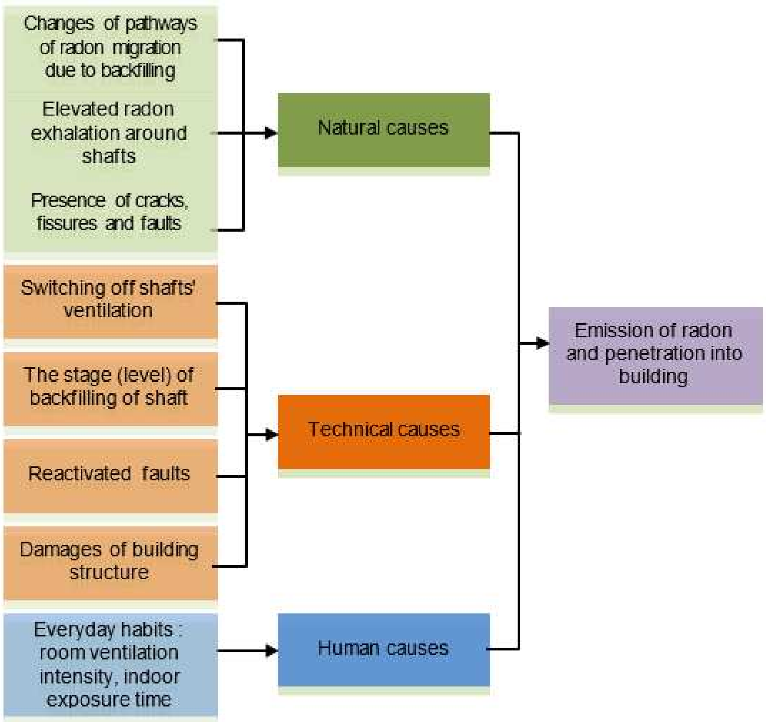
This stage represents the period before the mine closes. Shafts are opened and operating. Geodynamic processes due to coal extraction are influencing (changing) physical parameters of rocks.

Description of factors influencing risk associated with the emission of radon gas to the surface are presented below.



Stage 2

Period of mine closing. Shafts are under the procedure of closing. Coal extraction is stopped. The presentation of factors influencing the risk associated with the emission of radon gas to the surface and penetration into buildings is shown below.

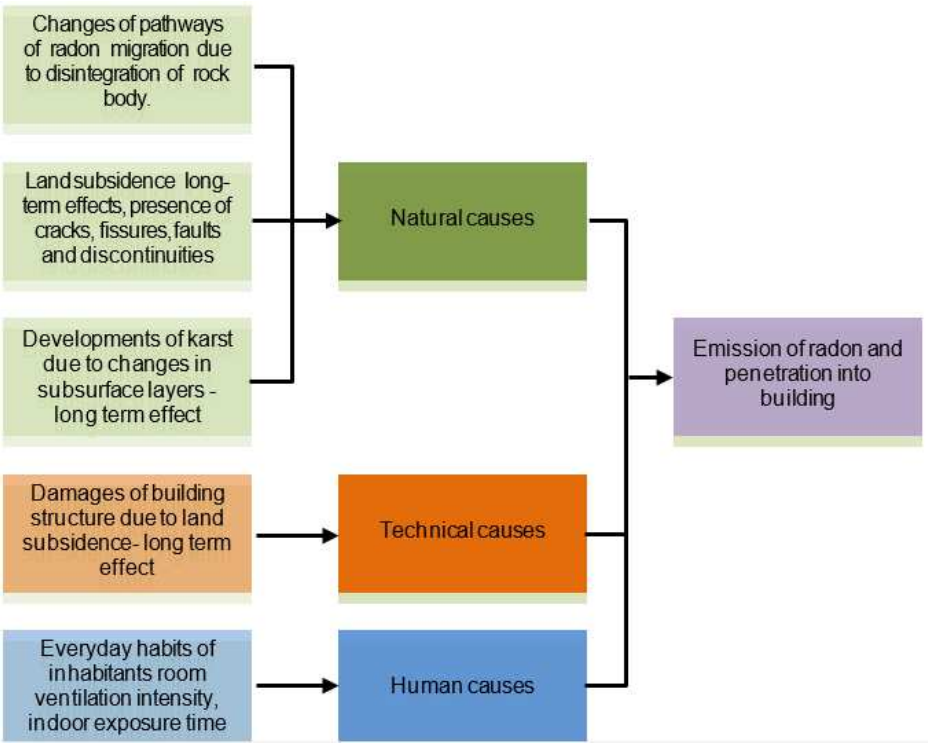


Stage 3

This stage represents the period of the mining termination and finalization of the all procedures connected with mine closure. Possible changes of radon migration are caused by long term phenomena such as the disintegration of subsurface layers due to land subsidence. It was found that total land subsidence in specific post-mining areas reached up to 20 m, causing linear discontinuous deformations of the surface in the form of fractures and fissures. Other long term effects enabling radon migration are changes in the depth of the groundwater layer, dewatering of rock body.

During this stage (lasting even several years after the closure of the mine) there may occur sudden land collapse, creating funnels and sinkholes or development of karst phenomena.

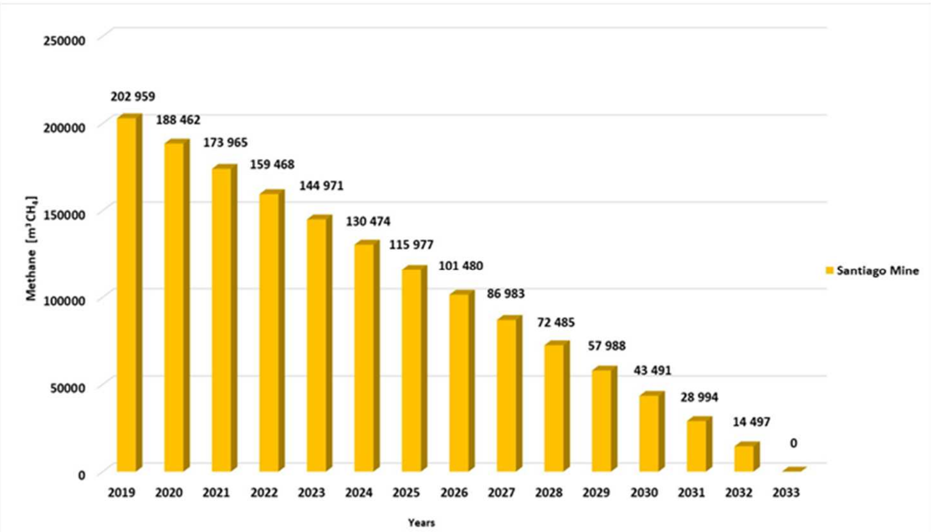
The presentation of factors influencing the risk associated with the emission of radon gas to the surface and penetration into buildings is shown below.



Risk assessment: Risk analysis

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 analysed.

Panels	SUB_N1_A3	F_N1_A2	F_N2_A10	Total
End of mining operations	2018	2018	2018	
Average absolute methane emission [m^3 CH_4/min]	0.5166	0.4935	0.369	1.3791
Methane emission into goafs of longwalls in consecutive years [$m^3 CH_4$/min]				
2019	0.144648	0.138180	0.103320	0.386148
2020	0.134316	0.128310	0.095940	0.358566
2021	0.123984	0.118440	0.088560	0.330984
2022	0.113652	0.108570	0.081180	0.303402
2023	0.103320	0.098700	0.073800	0.275820
2024	0.092988	0.088830	0.066420	0.248238
2025	0.082656	0.078960	0.059040	0.220656
2026	0.072324	0.069090	0.051660	0.193074
2027	0.061992	0.059220	0.044280	0.165492
2028	0.051660	0.049350	0.036900	0.137910
2029	0.041328	0.039480	0.029520	0.110328
2030	0.030996	0.029610	0.022140	0.082746
2031	0.020664	0.019740	0.014760	0.055164
2032	0.010332	0.009870	0.007380	0.027582
2033	End of methane emission into goafs in Santiago Mine			



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

Radon

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, 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).

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.

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.

In most countries the uniform method for assessing the risk of radon penetrating from the underlying soil or bedrock, based on determining the radon index of the building site, proposed by Czech scientists, is implemented – see table below.

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

Within the frame of MERIDA project both groups of measurements required (recommended) for risk evaluation were performed. The obtained results are the basis for the risk evaluation.

Risk category	Radon concentration in soil, C_{Rn} (kBq/m^3)		
Low	$C_{Rn} < 30$	$C_{Rn} < 20$	$C_{Rn} < 10$
Medium	$30 \leq C_{Rn} < 100$	$30 \leq C_{Rn} < 70$	$10 \leq C_{Rn} < 30$
High	$C_{Rn} \geq 100$	$C_{Rn} \geq 70$	$C_{Rn} \geq 30$
	Low permeability	Medium permeability	High permeability

Source: 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.

Risk assessment: Risk evaluation (methane)

Stage I

The Stage I concerns the period when the fans in ventilation shafts East and West are operating and the downcast shafts are opened.

During the risk evaluation simulations with VentGraph-Plus software were conducted.

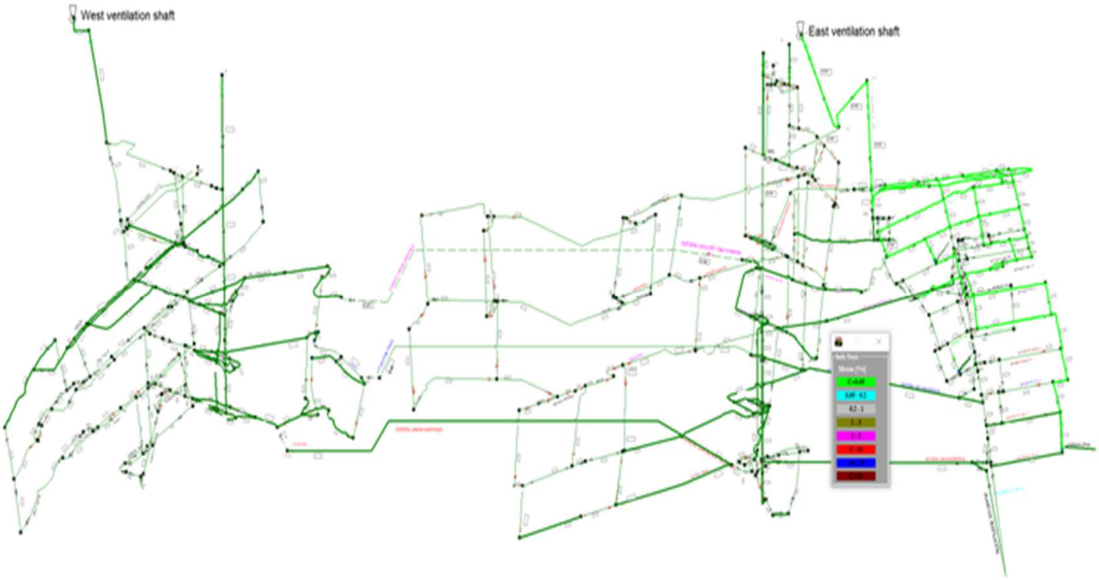
Due to the fact that the closure process in Santiago mine has not finished yet, the analysis of the gas hazard also includes an assessment of the risk of methane accumulation in the San Antonio and Santiago mines during the closure process.

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.

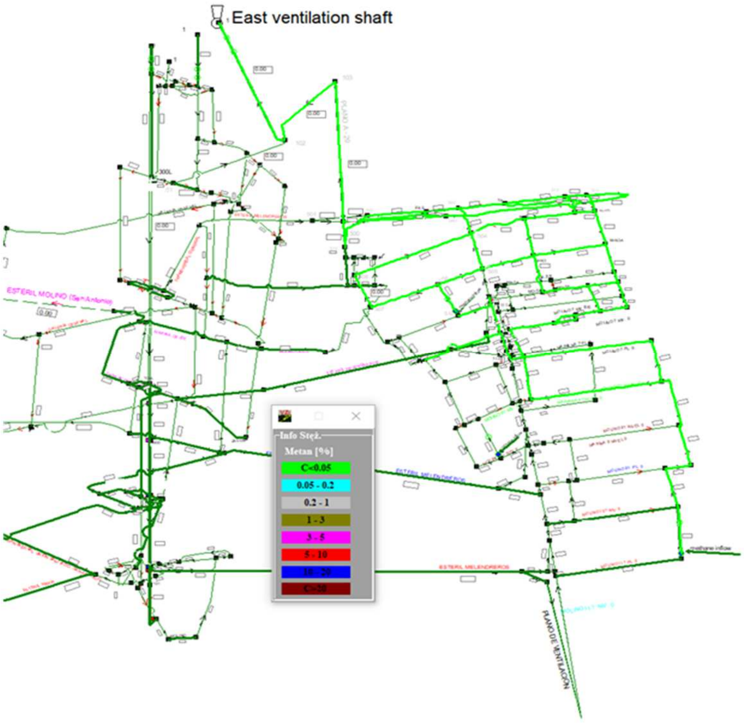
When the fan is not working, the flow of the gas mixture depends on natural depression generated by the methane distribution in mine workings.

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

The results of the simulation for 2033 i.e. the end of methane emission, are presented below for the whole ventilation network of San Antonio and Santiago mines.

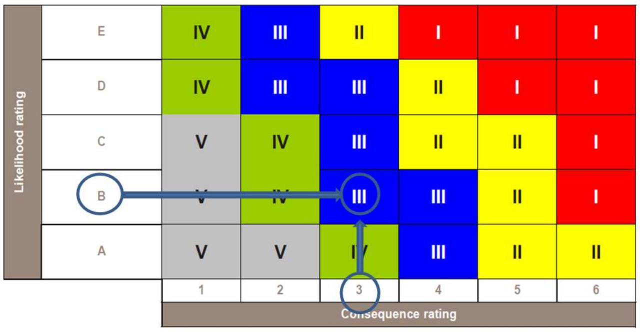


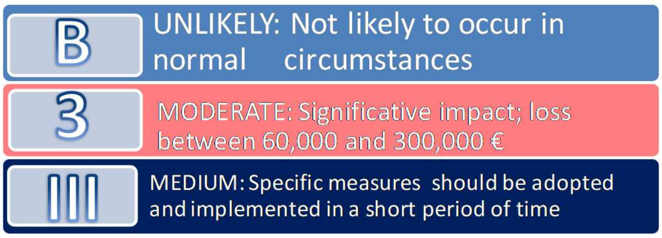
For East ventilation shaft:



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 below.

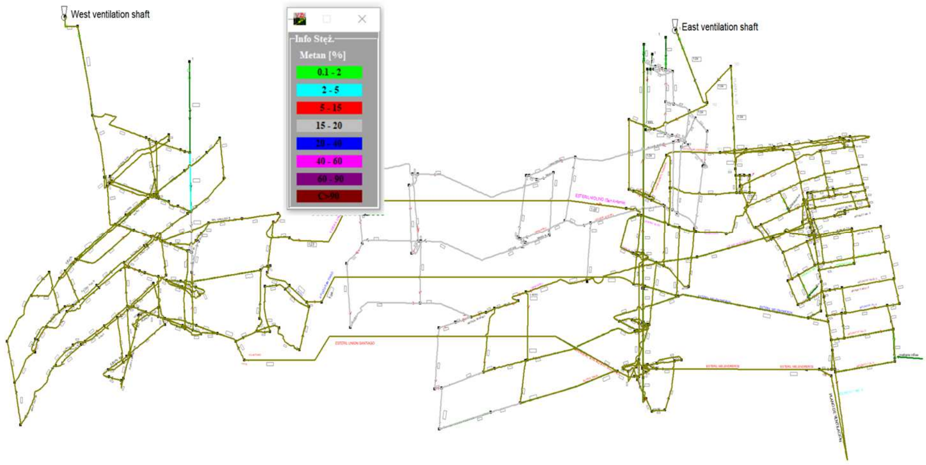




Stage II

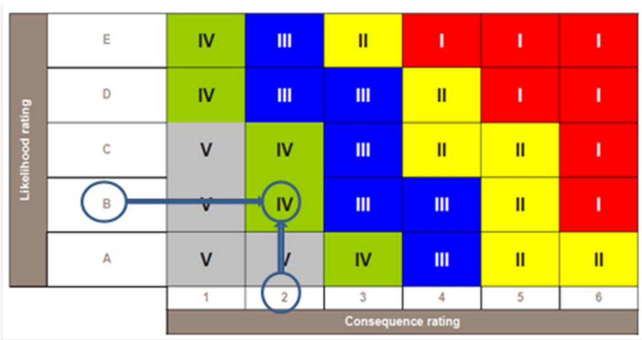
During the second stage, it was assumed that the fans in ventilation shafts East and West will stop operating in 2020. It was also assumed that the mine shafts will be closed (sealed), which will significantly limit the air flow in the mine. Both the volume of air and the direction of the flow of the methane-air mixture change in many mine workings. Such assumptions present the most unfavorable scenario of the development of gas risk on the surface of the closed mines.

The results of simulations for 2033, i.e. when the methane emission within the whole ventilation system of San Antonio and Santiago mines, are presented below.



The VentGraph-Plus simulation shows that the concentration of methane in the whole analysed area does not exceed explosion concentration (5%).

For risk of methane explosion on the surface, the results obtained by applying the proposed methodology are presented below.



B UNLIKELY: Not likely to occur in normal circumstances

2 MINOR: Very low impact; loss between 10,000 € and 60,000 €

IV LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.

Risk assessment: Risk evaluation (radon)

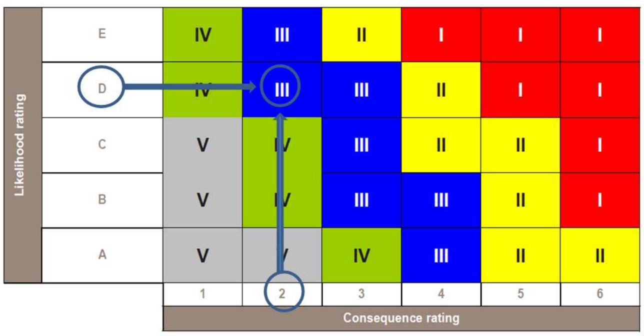
The period when the shafts are closed will be the only one considered. In the area of past mining activity, the important factor influencing the migratory ability of radon is the mining-induced transformations taking place in a rock mass, such as surface subsidence and tectonic discontinuities along fault zones generated by mining-induced geodynamic phenomena.

The underground tremors and bumps may still occur for some time after the coal mining operation has stopped. This process causes enhanced permeability in fault zones and may lead to increased levels of radon in soil gas. Another phenomenon observed in specific sites of post-mining areas is the development of zones of karst process causing the disintegration of rock body, which eventually enables the migration of radon.

The mining-induced dislocations and damages have a strong influence on the foundations of the building, creating cracks in floors and walls (see picture). The area in which long-term changes in the rock mass in the post-mining area can be significant. The boundaries of the basins of subsidence above the cavities caused by coal extraction significantly exceed the range of underground goafs.

It was assume that subsidence and destruction of buildings are still progressing for some time (maybe decades), after the mine has been closed. Probably elevated radon concentration will be measured in a larger number of buildings than in previous stages.

Based on the measurements and the phenomenon described above it was assumed that the concentration of indoor radon during the period of Stage 3 may increase by 100 Bq/m3. In such a case the total number of people in the area that probably would die annually because of lung cancer due to exposure to radon, is estimated at one (smoker and non-smoker), and estimated costs of medical treatment would be about 14 000 €.



Risk assessment: Proposed treatments

Accumulation of gas in the mine

To minimise the existing risk, it is necessary to take steps providing 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, there are applied intrinsically safe equipment.

In the mine workings explosion proof ventilation door are applied.

Emission of gases to the surface

To minimise the explosion risk gas leak detectors (An MTG-3000H) can be used in basements of the buildings located within 20 meters of the areas of possible gas migration. Its price is around 25 €. Thus, the mining company for all the buildings in the risk area can easily afford the cost. An MTG-3000H Gas Leak Alarm may be applied:

The residents shall be informed about the need to apply the detectors and it shall be verified by the inspectors checking the ventilation systems in the buildings located in the danger zones. The risk can be also mitigated by passive venting.

Radon

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): The new method for assessing the radon risk of building sites.- Czech. Geol. Survey Special Papers, 47. p., CGS Prague.), specific mitigation methods should be performed.

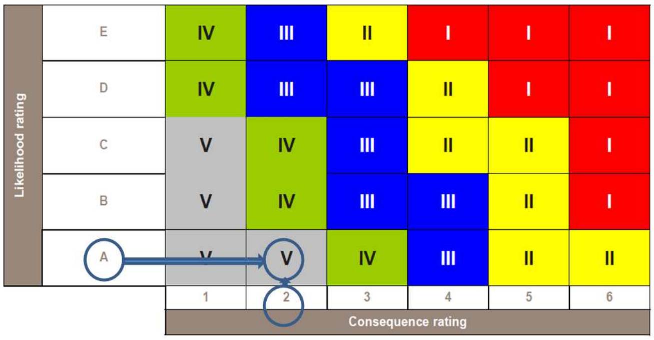
In this case, the proposed sufficient methods of reduction of radon gas concentration in buildings should be:

- 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;
- In case of elevated or very high indoor radon concentration, it would be necessary to install fans and pumps for removing radon from inside buildings.

Risk assessment: Performance forecast

Methane

The monitoring of the air composition, detectors and application of intrinsically safe equipment will lower probability. Also monitoring gas concentration in buildings located in the dangerous area and installing vent holes, the likelihood of a gas explosion will be significantly reduced.



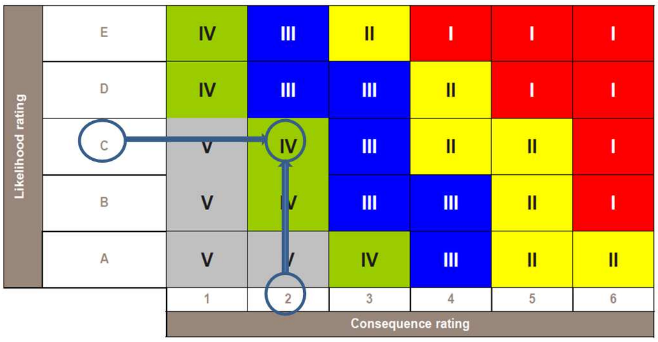
A — RARE: Probably it will never happen

2 — MINOR: Very low impact; loss between 10,000 € and 60,000 €

V — IRRELEVANT: No specific action is required

Radon

In most buildings, passive ventilation by opening windows will be a sufficient action. However, in chosen buildings most sophisticated measures will be advised. Through these actions, the risk associated with the emission of radon to the surface decreases to the lower level.



C — POSSIBLE: May occur at some time

2 — MINOR: Very low impact; loss between 10,000 € and 60,000 €

IV — LOW: No need to change the controls, but not very expensive measures should be implemented. Periodic monitoring should be considered.

Economic evaluation: Cost evaluation

In this analysis, we will only consider gas risk after the close of the mine. According to Deliverable 4.2, the likelihood for emission of gases to the surface was rated with a “B”, as this kind of rock mass deformation is not likely to occur in normal circumstances. In case that it happens, the impact will be minor (monetary loss can be estimated between 10,000 € and 60,000 €), and thus, there is no need to change the control, although not very expensive measures should be implemented and periodic monitoring should be considered.

To minimise the explosion risk gas leak detectors (An MTG-3000H) can be used in basements of the buildings located within 20 meters of the areas of possible gas migration. Its price is around 25 €/detector. Thus, the mining company for all the buildings in the risk area can easily afford the cost. The residents shall be informed about the need to apply the detectors and the inspectors checking the ventilation systems in the buildings located in the danger zones shall verify it. Passive venting can also mitigate the risk.

With an estimation of a 100 € including installation and a total of 200 building or small houses maximum that can be affected, the cost of the detectors will be:

Cost of detectors = 100 € x 200 = 20,000 €

Taking into consideration that they should be revised once a year, the yearly revision can be estimated in:

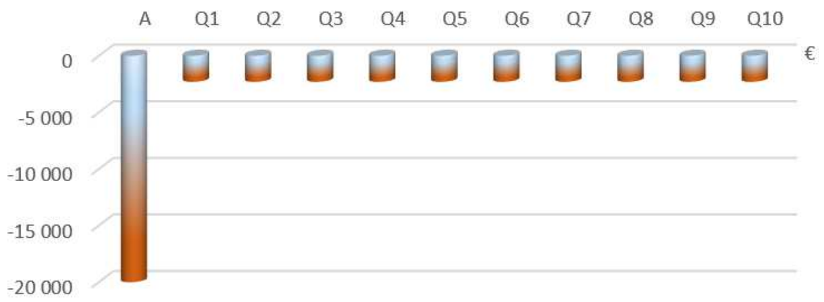
Yearly revision = 2,300 €

It can be estimated as 10 years the period that will be necessary to undergo the revision and/or substitution of detectors.

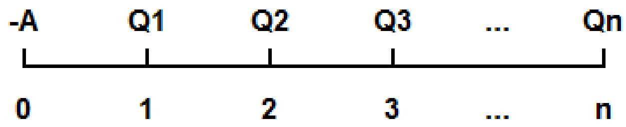
During the second stage, it was assumed that the fans in ventilation shafts East and West would stop operating in 2020. It was also assumed that the mine shafts will be closed (sealed), which will significantly limit the air flow in the mine. Both the volume of air and the direction of the flow of the methane-air mixture change in many mine workings. Such assumptions present the most unfavorable scenario of the development of gas risk on the surface of the closed mines.

Just by leaving a vent hole in each of the shafts and/or on the ventilation shafts, according to the results of the Ventgraph simulation, when they will be sealed, this will help a lot in fighting against the risk of methane accumulation in the basements of buildings within the mining area.

Considering these questions, the next Figure shows the cash flows for the gas risk treatment cost.



Economic evaluation: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 20,000 €

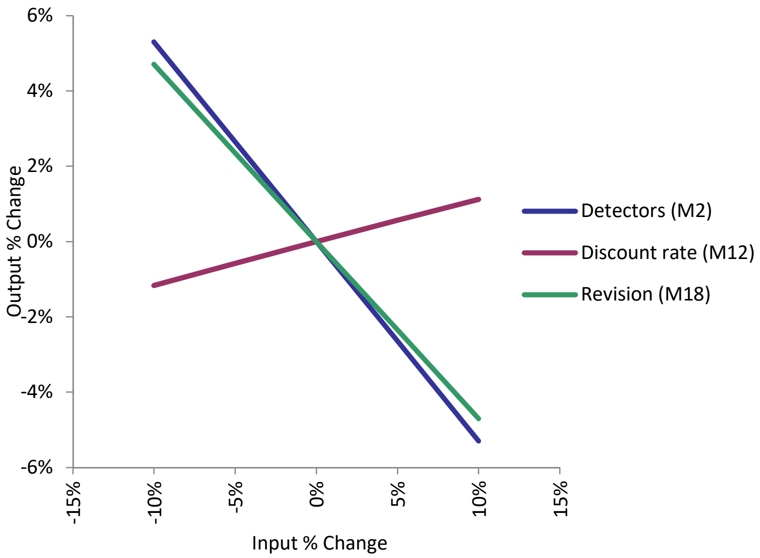
Q1, Q2, Q3, Q4, Q5... Q10 = -2,300 €

k = 5%; n = 10

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 gas risks will be:

NPV = - 37,760 €

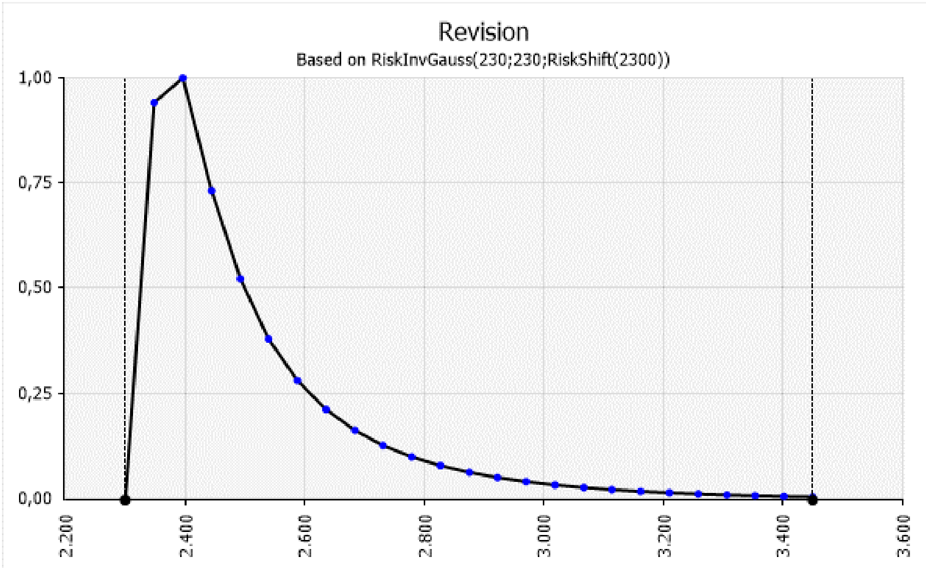
In order to estimate to which cost the MPV is more sensitive, a sensitive analysis was developed by means of allowing a ± 10% in every variable. The spider graph obtained was the following one:



Economic evaluation: Uncertainty analysis

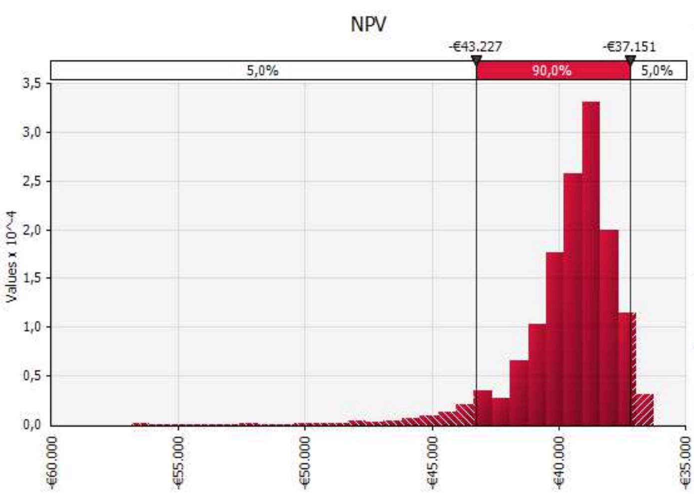
In this case, the NPV has almost the same sensitivity to both variables: the cost of detectors and the cost of yearly revisions. As it was said before, we will not consider in the calculations possible variations of the discount rate. Nevertheless, in this case the NPV presents low sensitivity to it.

In order to undergo an uncertainty analysis, the yearly costs of revision will use the same function as the one used for monitoring the piezometers: will be more rigorously modelled by an inverse Gaussian distribution centered in 2,300 € with parameters Mu = 230 and Lambda =230, in order to represent possible bigger prices but with a low probability:



On the other hand, the investment in detectors will be modelled again by a triangular function with parameters varying a 10% up and down.

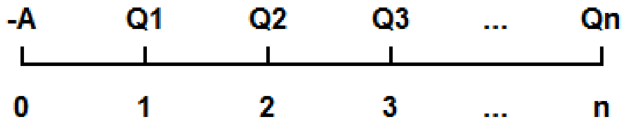
Running the Monte Carlo analysis, the NPV will be the following one:



	NPV
Cell	NPV!C1
Minimum	-€56.840,71
Maximum	-€36.214,44
Mean	-€39.536,55
90% CI	± €103,41
Mode	-€38.826,39
Median	-€39.133,88
Std Dev	€1.986,34
Skewness	-2,2418
Kurtosis	12,9741
Values	1000
Errors	0
Filtered	0
Left X	-€43.227
Left P	5,0%
Right X	-€37.151
Right P	95,0%
Dif. X	€6.075,99
Dif. P	90,0%
1%	-€46.904,92

So the NPV distribution obtained has a mean of -39,537 €, a minimum of -56,841 €, a maximum of -36,214 € and a standard deviation of 1,986 €.

Complete treatment cost: Financial provision



$$NPV = -A + \frac{Q_1}{(1+k)} + \frac{Q_2}{(1+k)^2} + \ldots + \frac{Q_n}{(1+k)^n}$$

A = 16,800 € + 223,000 € +20,000 € = -259,800 €

Q1, Q2, Q3, Q4, Q5 = -6,000 € -457,200 € -45,000 € = -510,500

Q6, Q7 = -3,000 € -45,000 € -2,300 € = -48,000

Q8, Q9, Q10 = -3,000 € -2,300 € =-5300 €

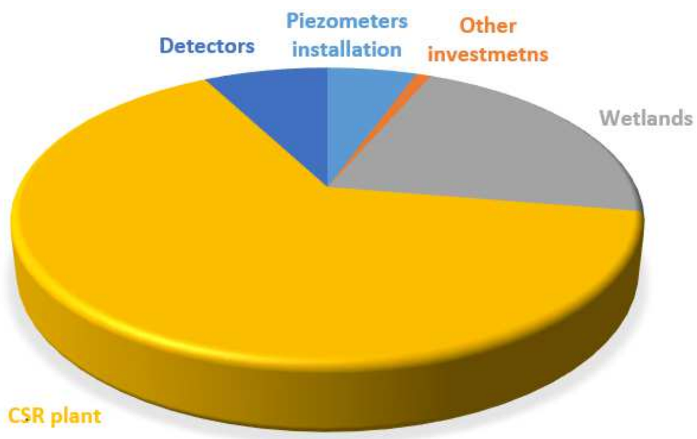
Q11, Q12… Q20 = -3,000 €

k = 5%; n = 20

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 will be:

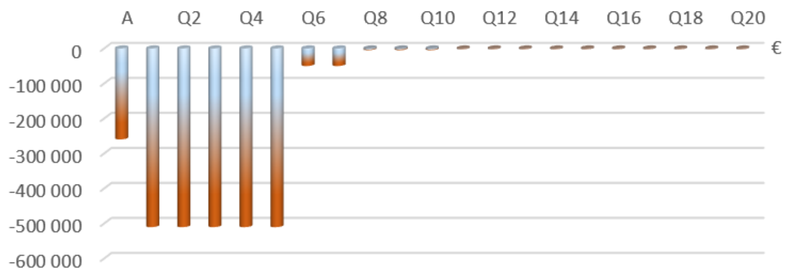
NPV = -2,564,408 €

The distribution of the investments can be clearly observed in the following figure, with the CESR plant in first place and the aerobic wetlands in second place. Thus, the investments needed to fight the surface water (environmental) risk are the most expensive of all.

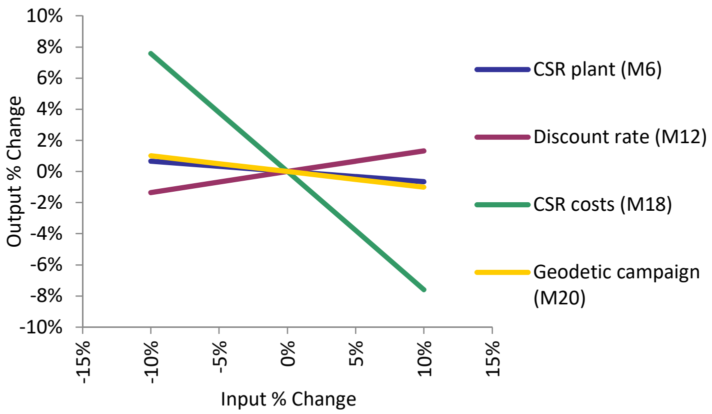


Complete treatment cost: Uncertainty analysis

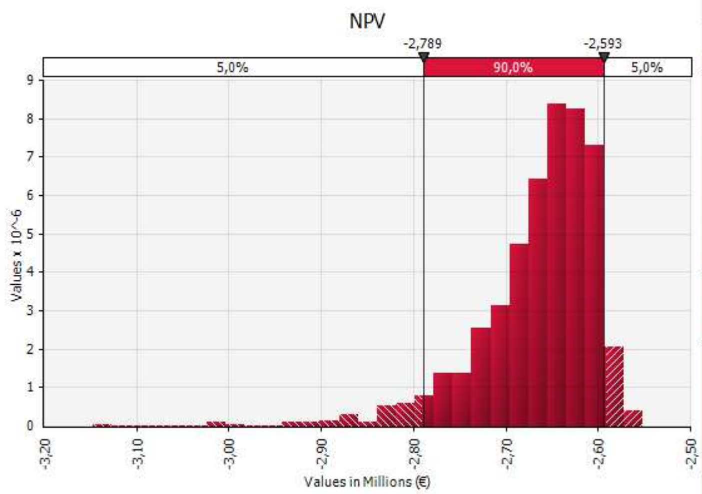
Addressing now the cash flows, the following figure presents the different cash flows during the 20 years considered:



Although quite logical, the following spider graph clearly presents the CESR operating costs as the ones to which the variable is more sensitive.



Running the Monte Carlo analysis, the NPV will be the following one:



	NPV
Cell	NPV!C1
Minimum	-€3.147.186,10
Maximum	-€2.552.024,28
Mean	-€2.664.337,25
90% CI	± €3.373,14
Mode	-€2.665.460,49
Median	-€2.649.095,70
Std Dev	€64.789,47
Skewness	-1,8695
Kurtosis	9,3046
Values	1000
Errors	0
Filtered	0
Left X	-€2.788.927,88
Left P	5,0%
Right X	-€2.593.177,30
Right P	95,0%
Dif. X	€195.750,57
Dif. P	90,0%
1%	-€2.892.678,44

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 €.

Conclusions

In first place, the ground water risk treatment costs were analysed. The different treatment options that should 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 mean NPV obtained was -68,910 €, being the variable to which the NPV has more sensitivity the monitoring of the piezometers, as they last for 20 years.

Secondly, the surface water risk treatment costs were analysed. The different pollution treatment options that should installed were: aerobic wetlands and a Cost effective Sulphate Removal (CESR) plant.

The aerobic wetlands will need a yearly maintenance during five years, the same period in which CESR will be operating incurring in operation costs.

The mean NPV obtained was -2,310,646 €, being the variable to which the NPV has more sensitivity the yearly operating cost of the CESR plant.

In third place, the ground movement risk treatment costs were considered. Only a yearly geodetic campaign should be developed during seven years.

The mean NPV obtained was -248,899 €.

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 mean NPV obtained was -39,537 €, having the NPV almost the same sensitivity respect the investment in detectors and the yearly revisions. The revisions were considered as necessary over a period of 10 years.

Concluding, the mean financial provision required for closure and post-closure for the selected Hulleras del Norte mines are estimated in -2,664,337 €. Nevertheless, according to the uncertainty analysis, this value could reach up to -3,147,186 €, so a conservative amount of -3,200,000 € will be considered.

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 it could be seen, 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 mine in Northern Spain.