

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Summary report
with
integrated Bow-Tie-Analysis

by

Projectgroup

"Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg"
(projectgroup GS-ZL)



on behalf of

Ministerie van Economische Zaken - The Netherlands

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Na-ijlende gevolgen steenkolenwinning Zuid-Limburg



Summary report with integrated Bow-Tie-Analysis

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Term	Description
after-effects	entirety of the mining-related effects that might emerge after the cessation of mining activity and that were assessed in the present study
aquiclude	sealing geological unit with a low hydraulic conductivity
aquifer	groundwater-bearing geological unit with a high hydraulic conductivity
backfill	loose material that is used to refill a stope for roof and wall support
backfill column	a column of loose material used to refill a mine shaft
crown pillar	a pillar above of an open stope that was left unmined for protection from overburden material collapsing into the stope
GNSS	Global Navigation Satellite System
ground heave	a process describing an upward movement of the land surface
hanging wall	the overlying geological layers
InSAR	Interferometric Synthetic Aperture Radar: a satellite-based radar technique that is used to observe surface deformation on a large scale
laying wall	the underlying geological layers

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Glossary

levelling profile	a regular array of benchmarks (commonly arranged in a line along a street) used for the periodic survey of ground movement
NPR	Nederlandse Praktijkrichtlijn
pillar	a layer or column of rock or coal that is left unmined to support the overlying rock strata
stope	an underground excavation from coal mining
suffosion	subterranean erosion of fine-grained material by flowing water
wetting	saturation of soil with water



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1 Objectives

In South Limburg coal mining has been carried out in an area of about 230 km² between the German coal mining district close to Kerkrade/Herzogenrath in the southeast and the Belgian border along the river Maas near Geleen in the northwest. The Dutch energy supply was largely based on this mining of coal in the South Limburg mining area before the discovery and exploitation of the oil and gas fields in Groningen and the North Sea.

The historic beginnings of Dutch coal mining date back to the 12th century, when close to the Wurm valley near Kerkrade the first excavations of coal directly outcropping at the surface were made. With the industrialisation in the 19th century the mining developed towards the northwest up to the river Maas, where the coal deposits are located at a greater depth below a thick overburden. Beginning in the 1960s, as a result of the discovery of gas in the Groningen area, the coal mines in the South Limburg mining district were no longer sufficiently profitable. As a consequence, the mines were closed one by one. In 1974 the last Dutch coal mine, the Julia mine near Eysgelshoven, was closed down. Since then, public awareness of the legacy of coal mining has gradually decreased.

After the last mine in the South Limburg area was closed in 1974, dewatering measures were kept up on the Dutch territory in order to protect the still active German mines operated by the German mining company EBV GmbH until 1994. Therefore, only a partial flooding of the Dutch mines took place. Following the closure of the last German mine in 1992, protective dewatering measures were halted in 1994. Since that time, mine water has risen in the whole South Limburg area, and has not reached a hydraulic equilibrium until now.

Following reports of damage to buildings in the former South Limburg mining district, which might be related to former mining, as well as the occurrence of the



sinkhole in Heerlen in 2011 („t’Loon“), a discussion of the possible long-term effects of coal mining began. The Ministerie van Economische Zaken (EZ) of the Netherlands initiated a project „Na-ijlende gevolgen steenkolenwinning Zuid-Limburg“, and commissioned a systematic study considering all future safety aspects with respect to the potential consequences of former coal exploitation in South Limburg.

The workplan for the study (“onderzoeksplan”) was elaborated by Staatstoezicht op de Mijnen (SODM, 2014). The main question that had to be answered on the basis of the study was formulated as follows: *„Hoe kunnen risico’s van de mogelijke na-ijlende gevolgen van der voormalige steenkolenwinning in Zuid-Limburg gedurende de komende 40 jaar zo optimaal mogelijk voorkomen, verminderd of beheersbaar gehouden worden?“*

The subjects, that had to be dealt with, were summarised as follows:

5.1 Samenbrengen van benodigde data

5.2 Deelonderzoeken per na-ijlend gevolg

5.2.1 Onderzoek naar bodemstijging

5.2.2 Onderzoek naar verzakkingen bij schachten

5.2.3 Onderzoek naar verzakkingen boven ondiepe winningen

5.2.4 Onderzoek naar vervuiling van grondwater

5.2.5 Onderzoek naar stijging van grondwater

5.2.6 Onderzoek naar vrijkomen van mijnogas

5.2.7 Onderzoek naar lichte aardbevingen

5.3 Overkoepelende risico-analyse

5.3.1 Prognose van de nog te verwachten mijnwaterstijging

5.3.2 Bow-Tie-Analyse van na-ijlende gevolgen

5.4 Overkoepelende analyse van monitoring/mitigatie/preventiemaatregelen

5.4.1 Onderzoek naar herstart mijnwaterpompen

5.4.2 Onderzoek naar heropenen ontwateringsgalerijen

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Based on a Europe-wide tender, the study was contracted out to a German-Dutch project group (projectgroup “na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg - „projectgroup GS-ZL“), which has comprehensive knowledge of the regional hydrology and ground movements, on the one hand, as well as extensive experience in the assessment of risks due to mine water rise and of the legacies of coal mining, on the other.

This report presents a summary of the results of each work package and leads to an overall risk assessment based on an integrated Bow-Tie-Analysis. Recommendations for actions, monitoring and preventive measures are the final output of this risk assessment.

These results may provide the basis for further action by the various Dutch authorities.



2 Project structure and procedure

Based on the work plan of the assignment, the project was structured along the lines of the different subjects that had to be investigated. For each subject a working group with technical specialists was established (Fig. 1). The specialists and institutions involved were as follows:

- Ingenieurbüro Heitfeld-Schetelig GmbH (IHS), Aachen (D)
- Witteveen & Bos, Deventer (NL)
with Pieter van Roijen und Bernhard Dost (KNMI)
- TU Delft, Geoscience & Remote Sensing
- GeoControl, Maastricht (NL)
- DMT, Essen (D)
- ahu AG, Aachen (D)

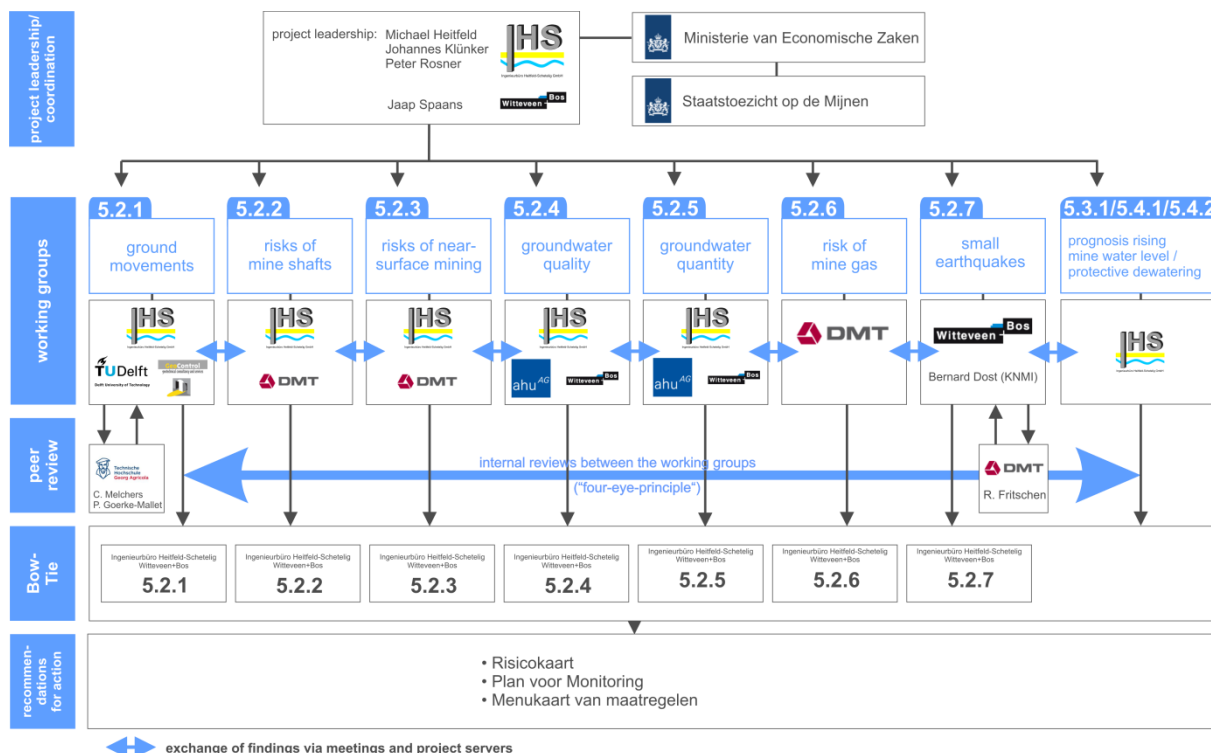


Fig. 1: Project team and project structure

Before the project started, the Dutch Geological Survey (TNO, Utrecht) was commissioned by the Ministry of Economic Affairs (EZ) with the task to search for and provide the data required for the project (subject 5.1 of the SodM work-plan). This data was passed on to the assigned project team in digital form and provided the basis for the research.

The various working groups summarised the results of their evaluations in separate interim reports. Each of these reports comprised a detailed discussion and assessment of the different hazards or risks arising from former mining activities that might evolve in the future or already exist.

The interim reports were subjected to an internal review. For particularly complex subjects, external experts were engaged as reviewers:

- for the topic „ground movements“
Prof. Melchers/Prof. Goerke-Mallet, TH Agricola, Bochum (D), and
Dr. Mütterthies, EFTAS Fernerkundung Technologietransfer GmbH,
Münster (D);
- for the topic „seismic activity“
Dr. Fritschen, DMT, Essen (D).

Comments and suggestions from the review processes were incorporated in the reports.

In the separate working groups, Bow-Tie-Analysis is used as the method to analyse risks per after-effect and to define mitigation and prevention measures. Bow-Tie-Analysis is a strong tool to visually clarify the risks and visualise possible measures associated with the seven effects or hazards. The power of a Bow-Tie-diagram is that in a single picture an overview is given of multiple plausible scenarios of the different effects that might lead to a detrimental impact (“Top Event”) and the different Consequences that might arise from this impact.

Figure 2 below shows a schematic representation of a Bow-Tie-Analysis. The knot of the Bow-Tie, i.e. the centre of the diagram, is formed by the incident or Top Event, which is connected to a certain hazard. On the left side, the various causes that may trigger an incident are summarised, i.e. the Threats. On the right side, the potential impacts from the Top Event are listed, i.e. the Consequences.

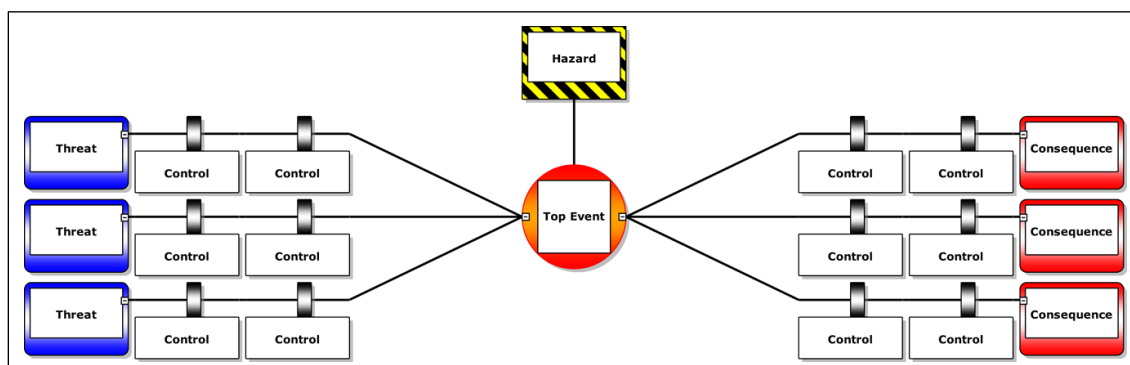


Fig. 2: Schematic representation of a Bow-Tie-Analysis

Subsequently, Controls can be added in between the Threats, the Consequences, and the Top Event. These can be either preventive, i.e. prevent a Threat from escalating into a Top Event, or mitigating, i.e. reduce the Consequences once the Top Event has occurred. Also, monitoring controls can be added to detect a Top Event or to direct preventive and/or mitigating controls.

The individual Bow-Tie-Analyses per working group are shown and described in the separate reports of each working group. These separate reports also give an indication of the potential impact areas on a map (Plans 1 to 7).

On the basis of the final reports of the separate working groups a comprehensive comparative risk analysis was carried out (an integrated “Bow-Tie-Analysis”, see Section 6). As a result, an integrated catalogue for monitoring and measures (Plan 8) was worked out. Within this context, the cost-benefit ratio was discussed.

3 General setting of the project area

3.1 Mine closure and the process of mine water rise

Between 1967 and 1974 the coal mines of South Limburg were closed, starting with the Maurits mine in Geleen, and ending with the Julia mine in Eygelshoven (Fig. 3). This marked the end of a once highly productive and profitable 150-year period for the mining industry. At its peak, there were nine privately owned mines (Neu Prick, Domaniale, Willem Sophia, Laura, Julia and Oranje Nassau I, II, III and IV) and four state-owned mines (Wilhelmina, Hendrik, Emma and Maurits).

With the successive closing of the mines, the pumping of mine water also ceased step-by-step. As all mines were connected to each other, the still productive mines had to be protected from the rising mine water in this period. Therefore, the connecting galleries to the already abandoned mines were closed by dams at the relevant levels. This allowed for a careful and controlled rise of water in the mining area.

The German mining company EBV GmbH continued the extraction of mine water from the Beerenbosch II shaft on the Limburg side of the border until 1994. This pumping was necessary to protect the still active German mines east of the Feldbiß fault from flooding.

In Flanders the mines continued operating for about 13 years after the last mine in the Netherlands was closed. But, in the period 1987 to 1992, these mines were also shut down (Waterschei and Eisden in 1987, Winterslag in 1988, Beringen in 1989, and, finally, Zolder in 1992).

In 1987 the pumping of mine water was stopped in the Belgian mine closest to the Dutch border (the Eisden mine in Maasmechelen). In 1994 pumping was also stopped in Beerenbosch II shaft. This caused the water level in the mines to rise gradually in large parts of Germany, South Limburg and Flanders.

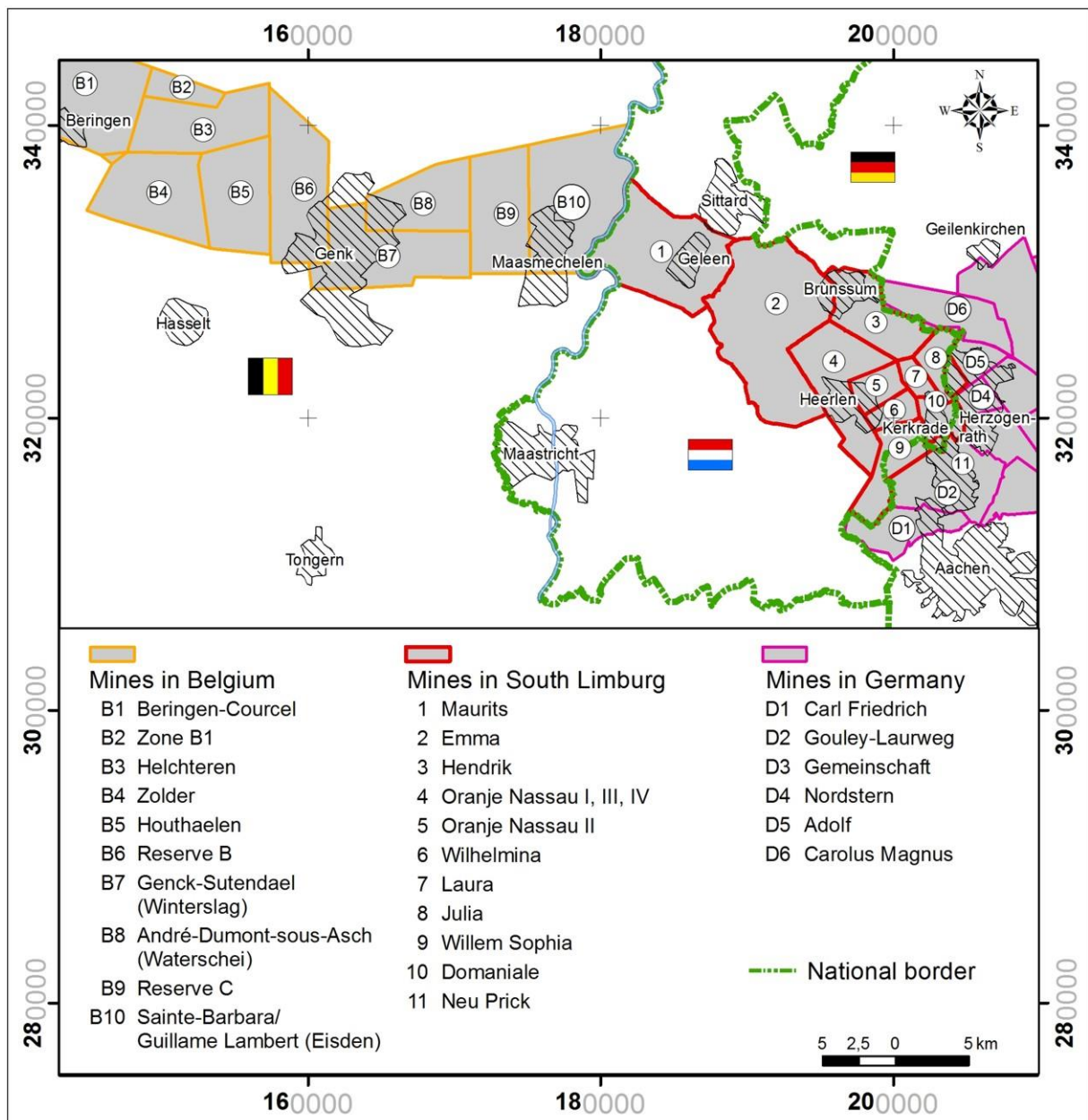


Fig. 3: Mines in South Limburg and adjacent areas of Belgium and Germany

Understanding the hydraulic structure of the mining district, as well as understanding the temporal progression of the mine water rise in different parts of the mining district is of particular importance for the understanding and interpretation of possible impacts due to the rise of mine water. Therefore, an outline of the hydrogeological structure of the mining district is given in Fig. 4.

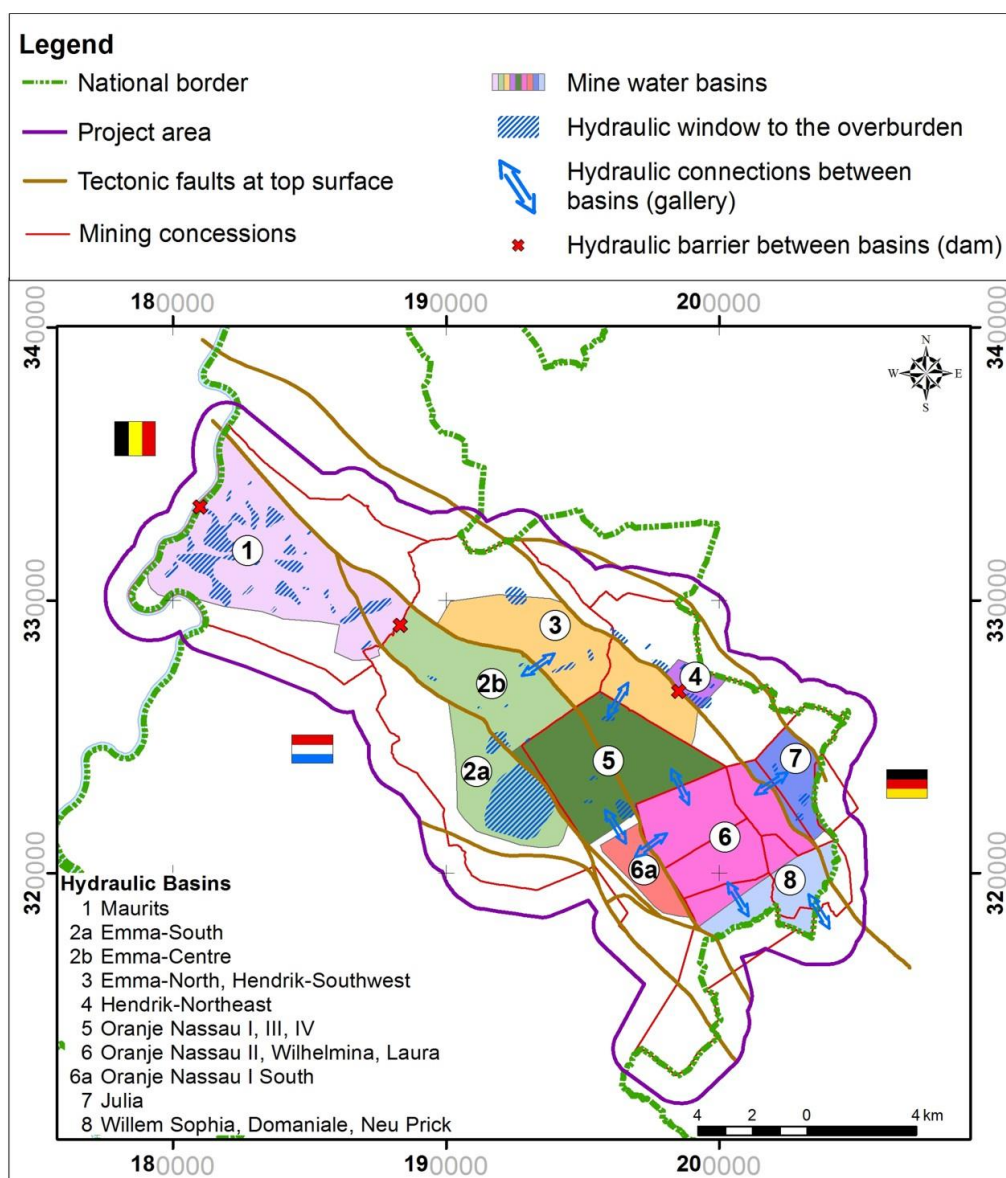


Fig. 4: Hydraulic structure of the mining district showing documented hydraulic windows to the overburden



In the productive period, all Dutch mines were connected to each other. Following the closure of mines, the connecting galleries were partly sealed by dams. The hydraulic interactions between the coal mines after the closure of mines are determined by the lowermost galleries that still connect the mines.

Until the rising mine water reached the level of these galleries, the rise took place in isolated basins. Once these galleries were reached, the isolated basins gradually merged into larger basins with a uniform mine water level. Only the Maurits coal mine (basin 1) and parts of the mine workings of the Hendrik coal mine (northeast of Feldbiß fault zone, basin 4) are not hydraulically connected by galleries to the other coal mines of the South Limburg mining district. However, even though the connecting galleries between the Laura coal mine and the Julia coal mine were sealed by dams in the 1970s, the progression of the mine water rise suggests that there is a hydraulic connection between these mines.

Also the Dutch concessions Domaniale and Neu Prick are hydraulically connected to the German mine Gouley-Laurweg, which was closed in 1969.

The progression of the mine water rise is illustrated by Fig. 5. In principle, three phases of mine water rise can be distinguished:

- In the first phase, mine water rose to different levels in parts of the separate basins due to the successive abandonment of coal mines in South Limburg (1967 - 1974).
- In the second phase, mine drainage at the Beerenbosch II shaft (Domaniale coal mine) was resumed in 1973 at a level of -241 mNAP in order to protect the coal mines of the Aachen mining district. Until 1988, the mine water levels in the different basins of the South Limburg mining district rose independently until they reached the level of a connecting gallery to a neighbouring basin. Then, all the mine water flowed to the Domaniale mine via the system of in-

terconnected basins. The mine water remained at these levels in the whole area, and all mine water was pumped from the Beerenbosch II shaft to the Wurm river.

In this second phase, three main basins developed, each characterised by a homogeneous mine water level at levels around -61 mNAP (northern main basin with basins 2, 3 and 5, as shown in Fig. 4), -120 mNAP (central main basin with basins 6a, 6 and 7) and -214 mNAP (southern main basin, basin 8).

- The third phase started with the terminal cessation of the dewatering measures at the Beerenbosch II shaft (and the Von-Goerschen-shaft in Würselen, Germany) in January 1994. Within one year, a more or less unique mine water level developed in each of the three main basins. Since then, the mine water level has been rising at a more or less uniform level throughout the whole area of the South Limburg mining district (except basins 1 and 4).
- Due to the limited hydraulic connection, a slightly greater difference of the mine water levels developed between the Julia coal mine and the rest of the mining district; however, the difference continues to decrease.
- Thus far, there is no definite knowledge about the mine water levels within both the Maurits coal mine (basin 1) and the Hendrik NE basin (basin 4).

For the Maurits coal mine (basin 1), the continuing rise of groundwater levels in the overburden (Maastricht limestone) is shown by data from a deep piezometer in the city of Stein. These data indicate that also in this area the rise of mine water is still continuing.

Today, the rise of mine water is being monitored in five shafts. These five shafts are situated in the main hydraulic basins (Fig. 6). The data that these monitors provide indicate that the coal mines of Oranje Nassau I, III and IV and Julia (in the northwestern and central part of the South Limburg mining district) have been completely flooded (Fig. 6).

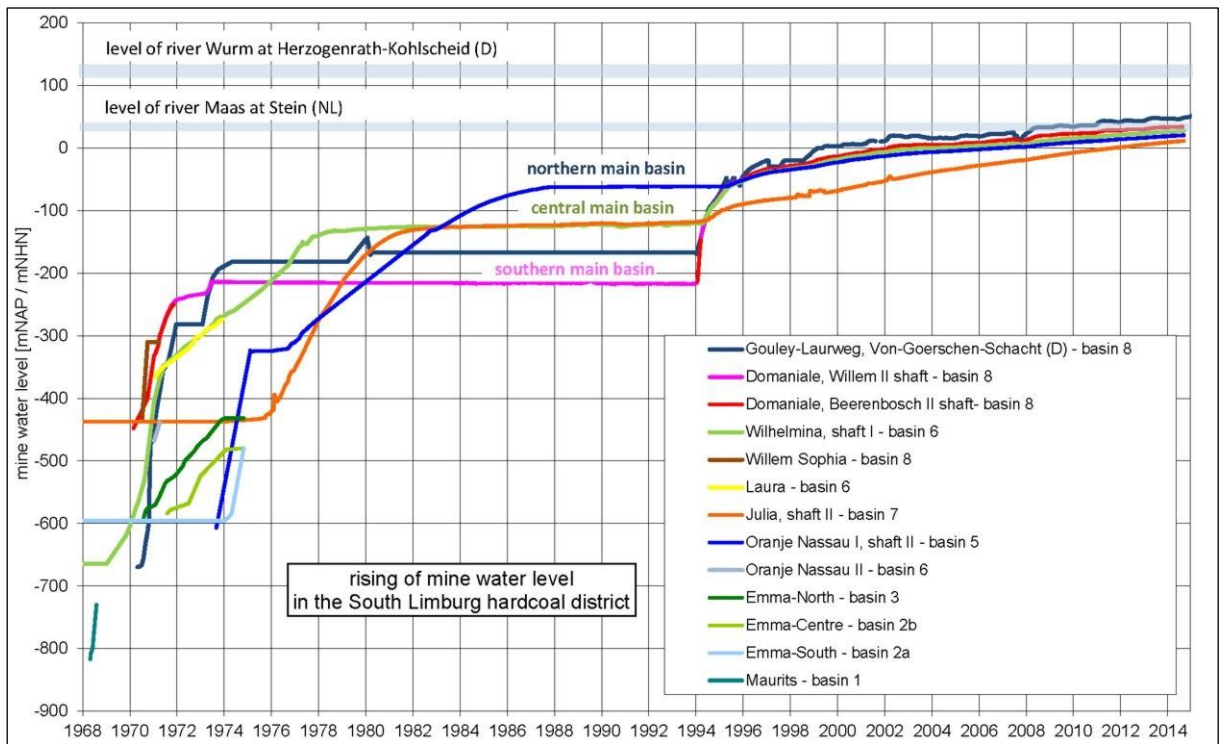


Fig. 5: Rising mine water levels in the South Limburg coal district

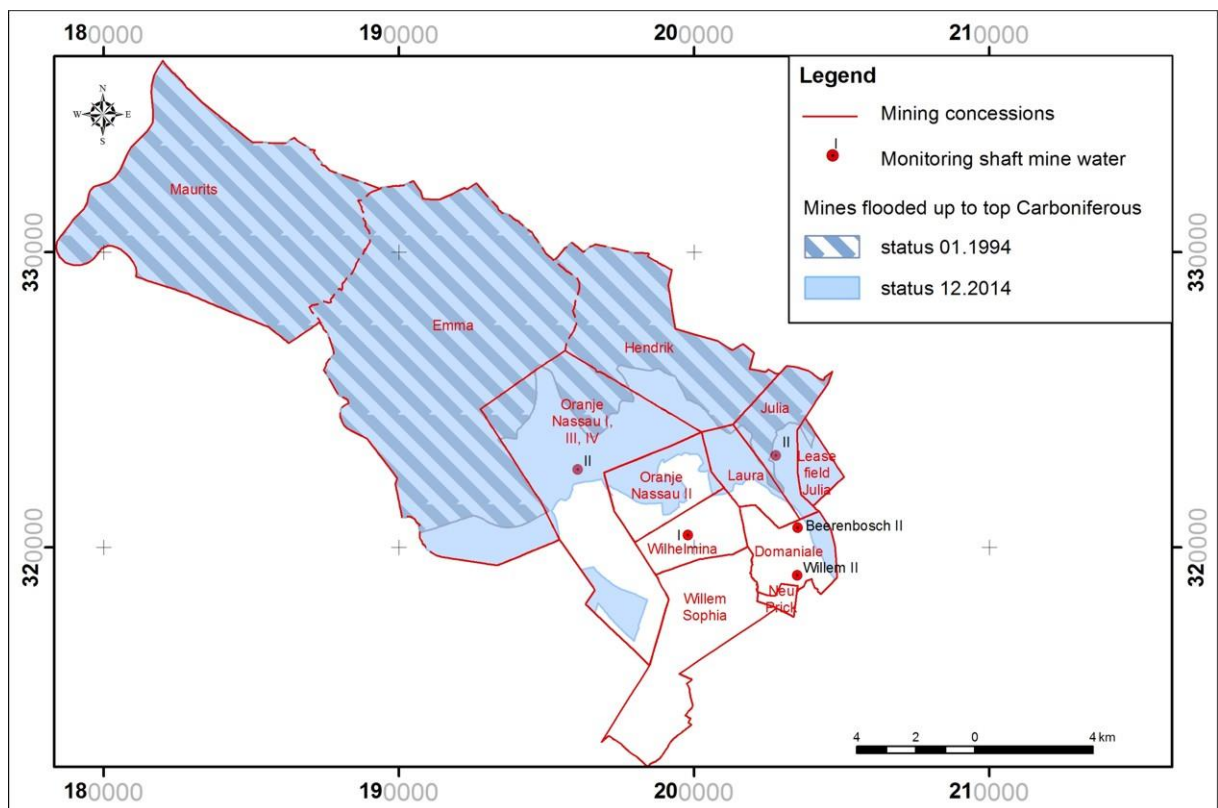


Fig. 6: Flooded areas in the Dutch mines in 1994 and 2014

In these areas, the mine water levels in the coal-bearing bedrock have already reached the overburden level. In parts of the southeastern mine district, mine workings are still situated above the current mine water level (12.2014). In these areas the mine water level currently lies below the base of the overburden.

3.2 Structure of the underground

The development and the extension of the coal mines in South Limburg are mainly dependent on the distribution and the structure of the coal-bearing bedrock layers from the Carboniferous period.

The Carboniferous bedrock is built of a cyclic sequence of predominantly shale, claystones and sandstones with coal seams. The coal-seam-bearing Upper Carboniferous ends with an extended eroded layer. Below the coal-seam-bearing Upper Carboniferous, there is a 600 to 700 m thick formation known as the Namurian. This formation forms a hydrological barrier between the upper layers and the deeper layers of the Kohlenkalk (Lower Carboniferous) and the Massenkalk (middle Devonian). These limestone formations form a deep saline groundwater reservoir.

The mining district of South Limburg is located on the northwestern flank of the great tectonic unit called the Venn Anticline. The Carboniferous layers, in general, dip slightly to the Northeast; the coal-bearing layers crop out at the top of the Carboniferous along the southwestern border of the mining district. Due to the tectonic compression, there are numerous SW-NE striking anticlines and overthrusts (from NW to SE: the anticline of Puth, the 70 m fault, the anticline of Waubach /the Oranje fault, Willem fault). These are of importance to the structure of the Carboniferous bedrock and the distribution of mine workings (Fig. 7).

Only in the Kerkrade area, the southeastern part of the mining district, the Carboniferous is characterised by tight folding. The intensity of that folding decreases quickly towards the northwest. Hence, the coal-bearing layers in the central and northern parts of the mining district are mainly flat dipping. Only in the vicinity of the anticlines of Puth and Waubach are the coal-bearing layers locally folded.

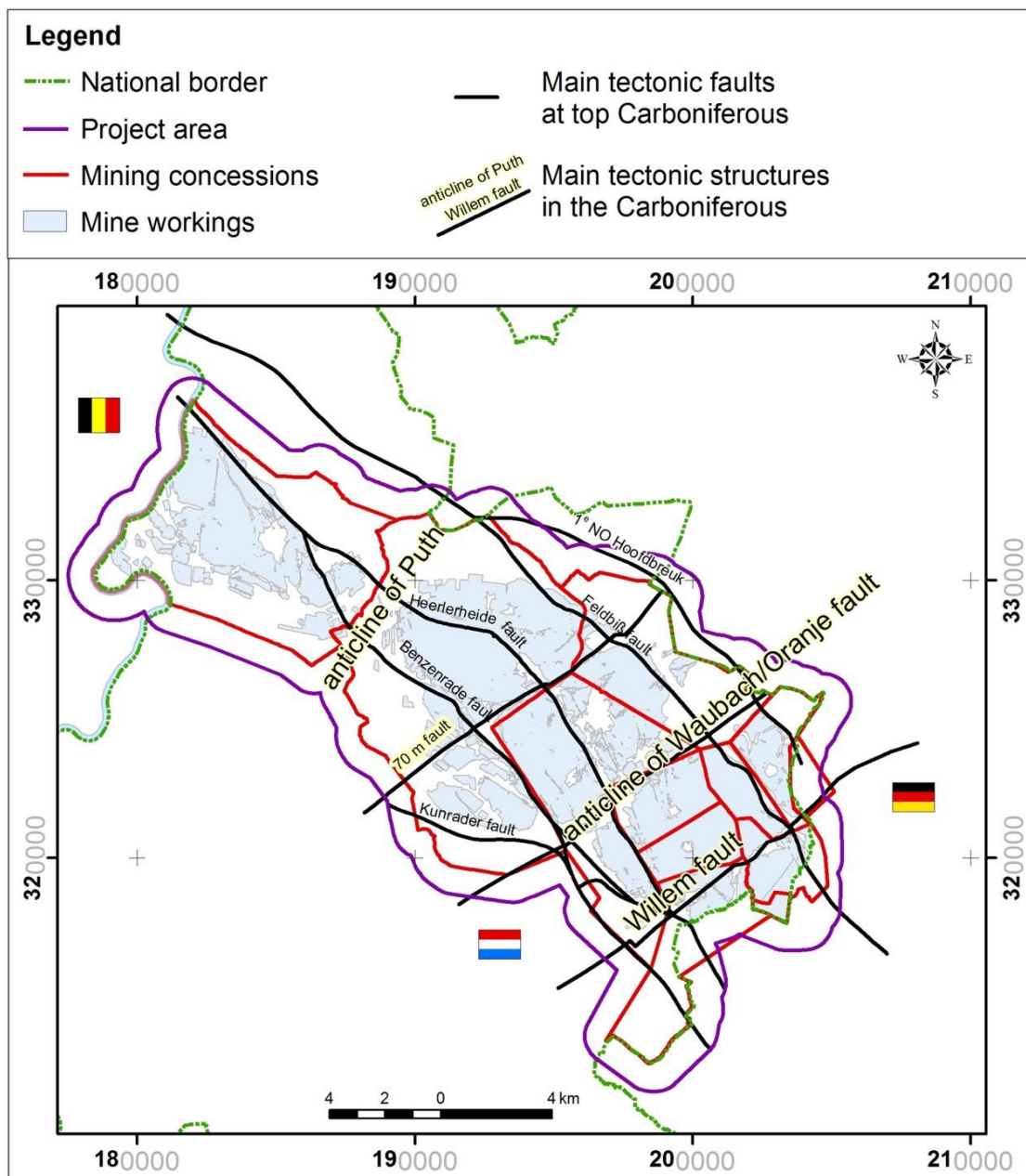


Fig. 7: Main tectonic structures of the Carboniferous basement

Almost perpendicular to the major SW-NE- trending anticlinal structures, there is a system of three main NW-SE orientated faults: the Benzenrade fault, the Heerlerheide fault, and the Feldbiß fault. These faults run through the overburden to the surface and divide the study area into three main hydrogeological units with different hydrogeological characteristics in the level of the overburden (HY I / HY II / HY III, HY IVb in Fig. 8).

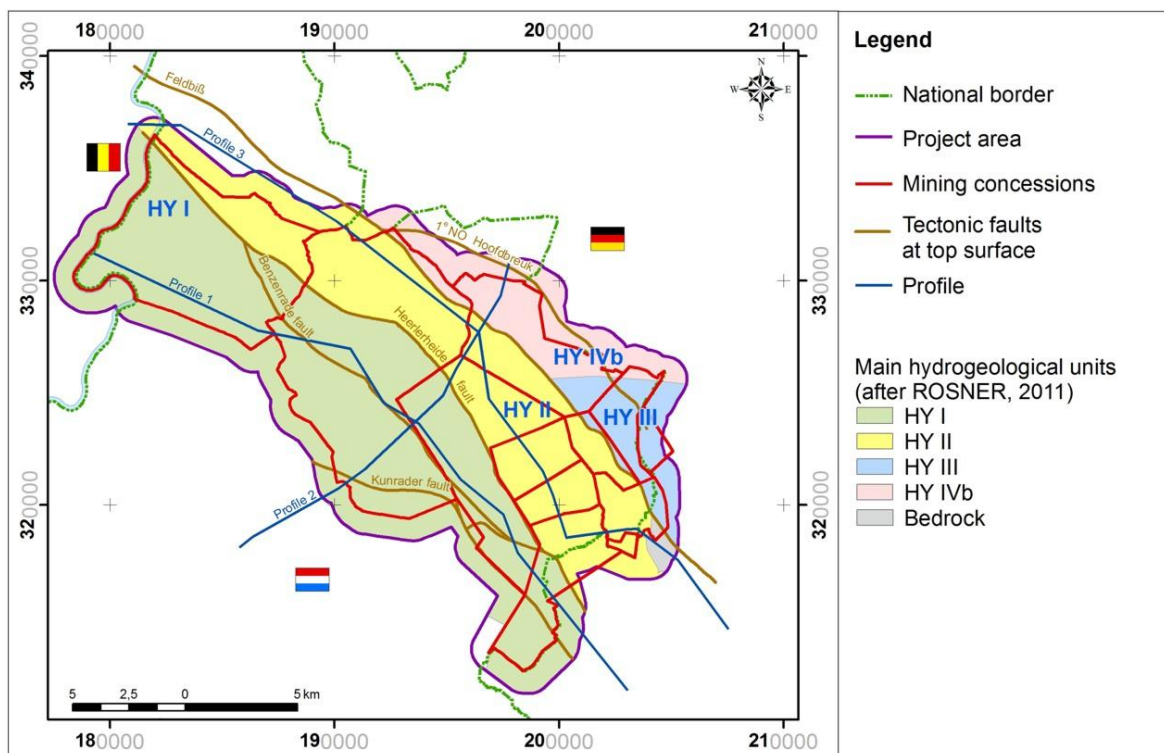


Fig. 8: Main fault zones and main hydrogeological units

The area southwest of the Heerlerheide fault (HY I) is characterised by Cretaceous sediments (limestone). In the central area (HY II) Cretaceous limestone only exists in the northwestern part (in the Emma concession). Elsewhere, Tertiary sediments (sand, clay, brown coal) dominate.

The surface of the Carboniferous formation and the oldest layers of the overburden gently slope downwards, in general at about 1° to 2°, in a northwestern direction (Fig. 9). Near the German border, the Carboniferous formation is covered by

less than 40 m of young sediments. In the western part of the Maurits mine, the Carboniferous formation is covered by up to 400 m of younger deposits. The sloping surface of the Carboniferous formation and the overburden in the north-western direction are shown in Figs. 10 and 11. The offset of the top of the Carboniferous bedrock at the main tectonic faults to the NE is shown by profile 2 in Fig. 12.

The hydrogeological system of the overburden is characterised by a complex layering of several groundwater-bearing layers (like limestone and sand) and sealing layers (like clay) from the Cretaceous to the Quaternary formations. In the southwestern part of the mining district, southwest of the Heerlerheide fault, the Cretaceous limestones are the most important layers from the hydrogeological point of view (HY I in Fig. 8). They form a deep second groundwater reservoir below the groundwater reservoir near the surface in the Tertiary and Quaternary sediments.

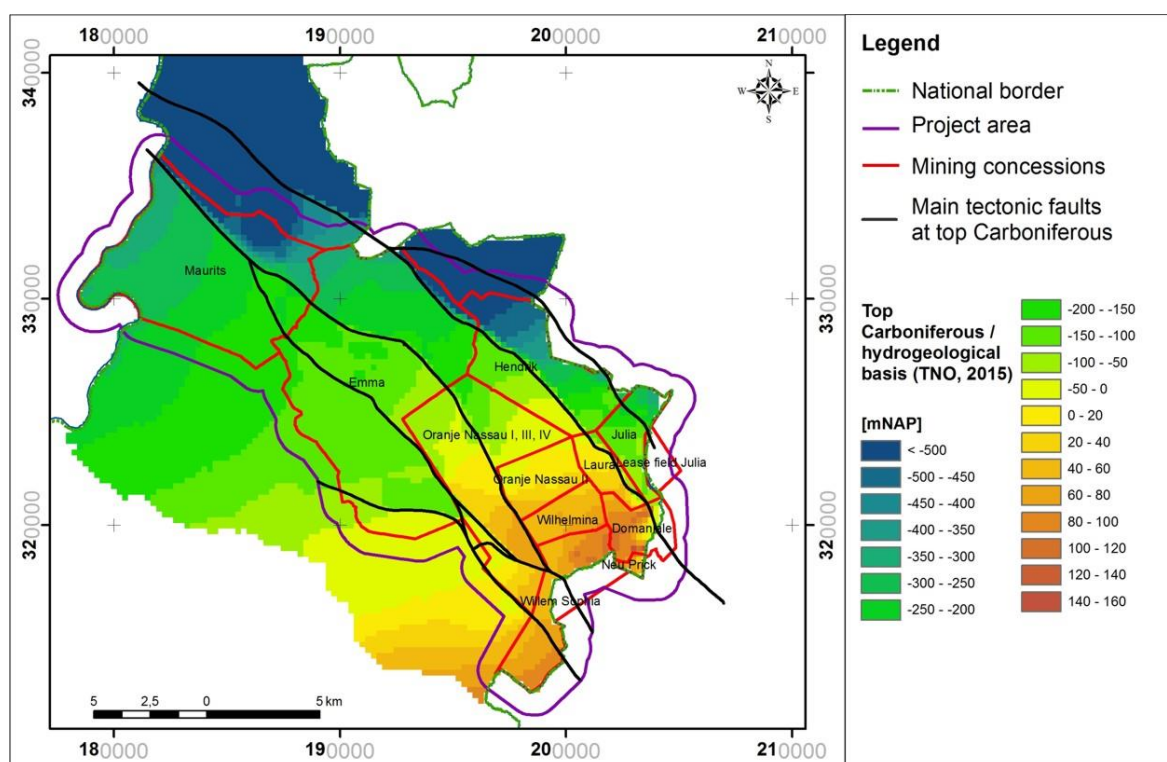


Fig. 9: Top Carboniferous/hydrogeological basis according to TNO (2015)

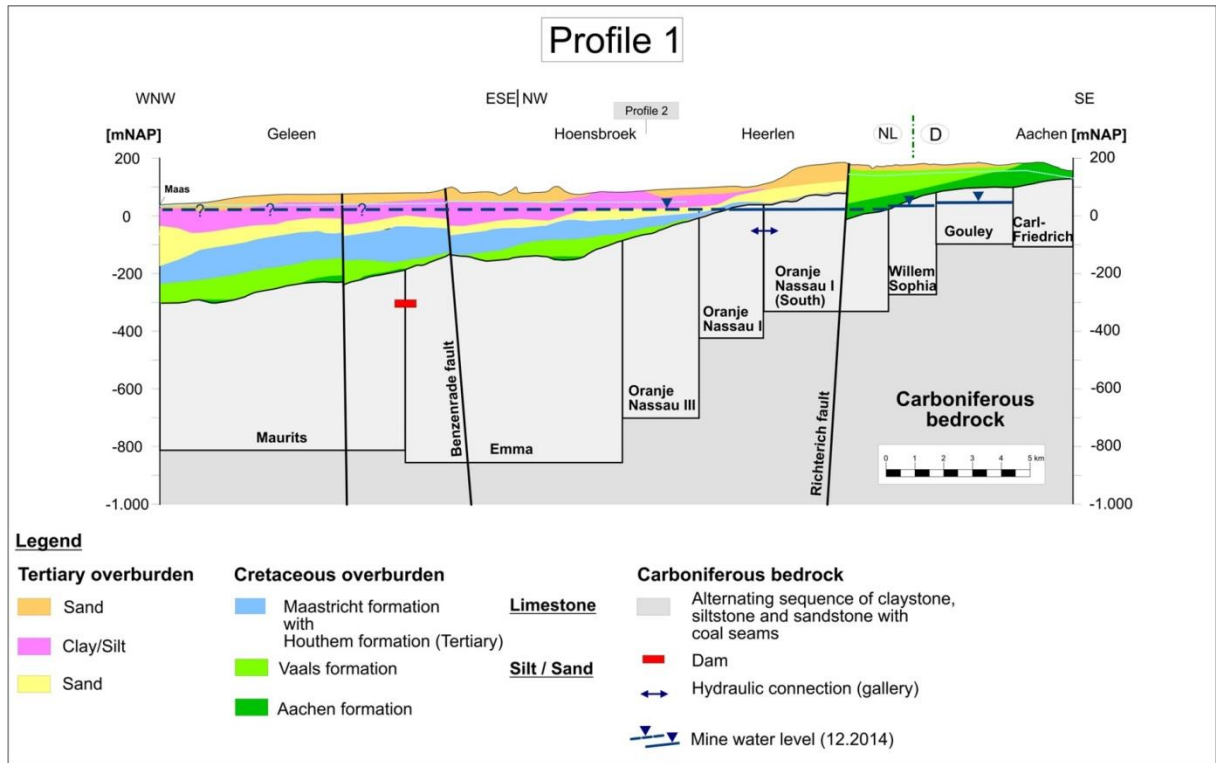


Fig. 10: NW-SE cross-section profile 1 (for the location of the profile, see Fig. 8)

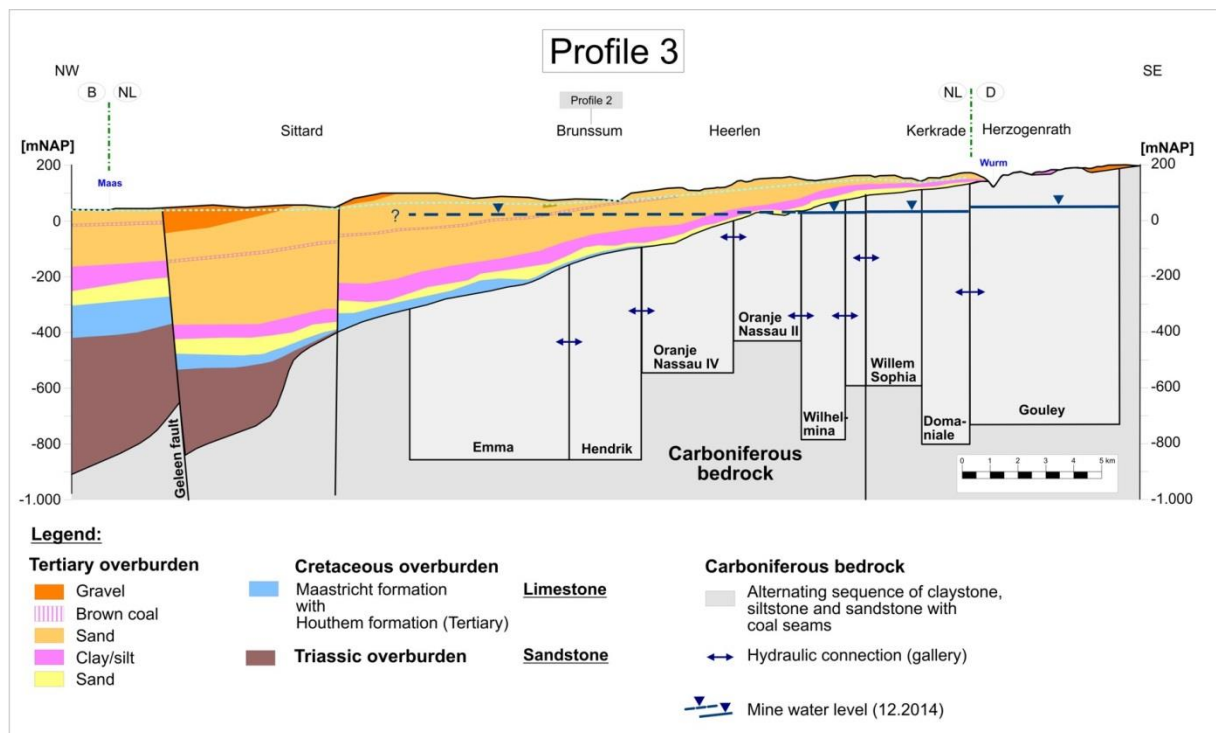


Fig. 11: NW-SE cross-section profile 3 (for the location of the profile, see Fig. 8)

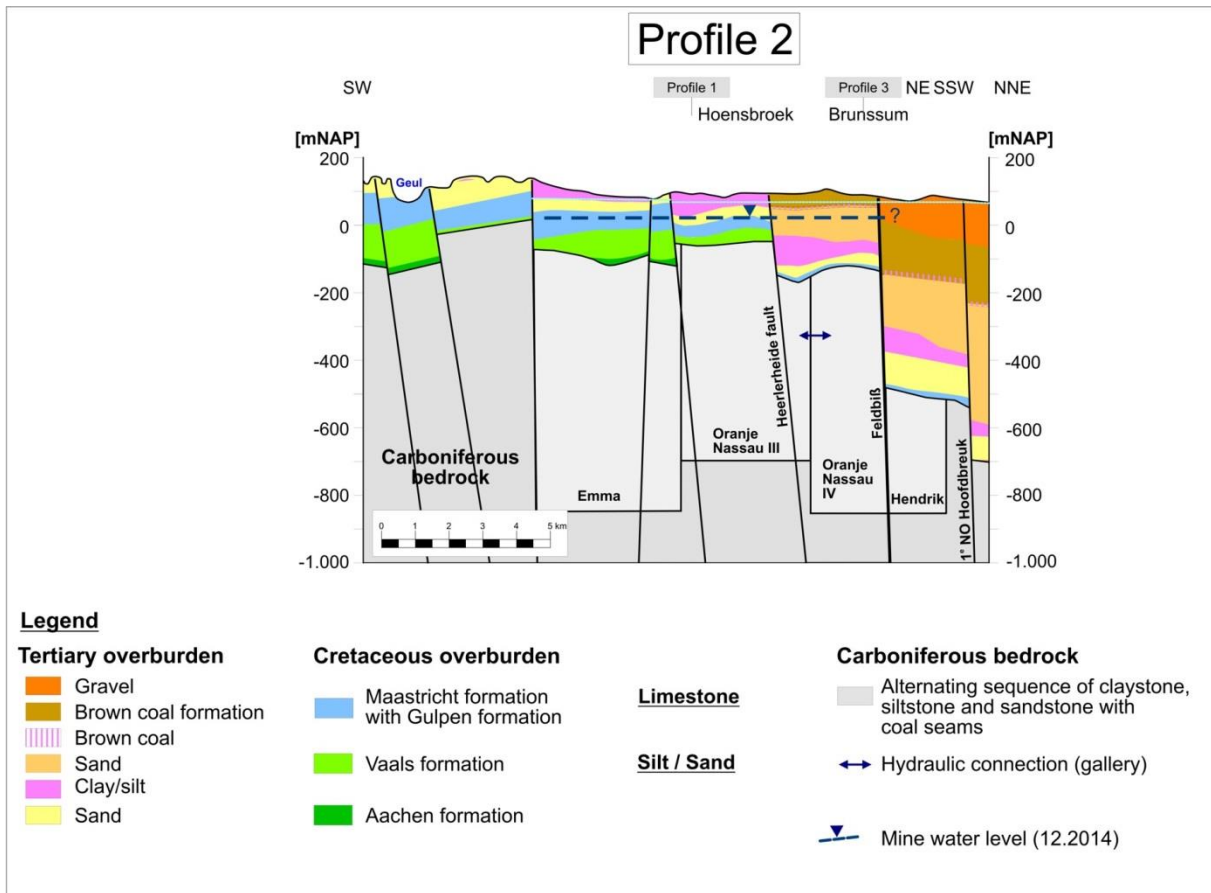


Fig. 12: SW-NNE cross-section profile 2 (for the location of the profile, see Fig. 8)

Northeast of the Heerlerheide fault (HY II, HY III and HY IVb in Fig. 8) Tertiary sediments dominate and form a uniform groundwater reservoir in the overburden together with the Quaternary sediments.

3.3 Mining relicts

Mining was carried out extensively across the whole area of the South Limburg mining district; however, mining intensity varied with the natural formation of coal seams (Fig. 7).

In the area of Kerkrade numerous coal seam outcrops at the surface of the Carboniferous bedrock appear due to the intense folding of the Carboniferous bed-

rock. This special tectonic situation is of some importance for the potential impacts from historical near-surface mining (see Subsection 4.3). In parallel with this, the Tertiary and Quaternary sediment cover is no thicker than 40 m. In the Wurm valley, the coal seams can even be found outcropping at the ground surface (Fig. 11).

Northwest of Kerkrade, the folding is less distinctive; hence, most coal seams are found to be flat dipping. However, there is a vertical displacement of the coal-bearing bedrock towards greater depths along the main fault zones. In conjunction with this, the thickness of the overburden increases.

In general, the major fault zones were a delimiting factor for mining. Furthermore, little to no mining has taken place in the vicinity of the anticlines of Puth and Waubach owing to a local disturbance of the Carboniferous structure and the disappearance of coal seams. The same holds for the Willem Fault in the border area between the Willem Sophia/Domaniale and Wilhelmina coal mines.

The first mining activities are documented to have taken place close to the German border in Kerkrade in as early as the 12th century (“Project area 1” in Fig. 13). In this area, the “historical near-surface mining” in the early years of coal mining focused on the near-surface coal deposits. Over time, mining activities advanced to greater depth.

For dewatering the early near-surface mines close to the Wurm valley, dewatering galleries were excavated starting from the bottom of the Wurm valley. These galleries were slightly inclined which allowed groundwater to be drained from the mines to the surface without pumping. Today, these historical dewatering galleries from the historical mine workings in the Kerkrade area run across German territory to the Wurm valley. The former portals (i.e. the outlets of the dewatering galleries where mine water flowed out at the ground surface) are now

broken and their functionality with regard to drainage is unknown. Therefore, it is not certain whether these galleries still maintain an adequate capacity for drainage (i.e. limit mine water rise) given the case in which the mine water reaches the level of the Wurm valley.

Coal seams were mined below a residual crown pillar (i.e. the thickness of the bedrock layer that remained between the mined coal seam and the overburden) of, in general, less than 20 m. In some rare cases, mining activities even reached the surface of the Carboniferous bedrock. Because of the near-surface mining activity, residual voids have to be expected close to the ground surface. Often, the layers above these voids are not thick enough to establish a stable vault. These are the situations where sinkholes might develop.

The historical near-surface mining is restricted to the Domaniale and Neu Prick concessions in the southeast of the mining district. In this area, numerous historical mine shafts are documented (Fig. 13). The abandonment of these shallow “historical” mine shafts was not regulated; hence, there is hardly any documentation of the abandonment, or even on the exact location of “historical” mine shafts.

The Industrial Revolution in the 19th century led to a higher demand for coal. Along with more advanced techniques, mining activities extended towards deeper coal deposits in the northwest. Until the closing of the South Limburg coal mines in the 1960s and 1970s, mining activities spread across the whole South Limburg mining district (Fig. 13), and reached down to a maximum level of approximately -780 mNAP in the Maurits and Emma mines; to approximately -540 mNAP in the Julia mine; and to approximately -730 mNAP in the Domaniale mine. In the vicinity of the main anticlines, mining was restricted to the shallower levels (e.g. -550 mNAP in Oranje Nassau II) (see Fig. 10 - Fig. 12).

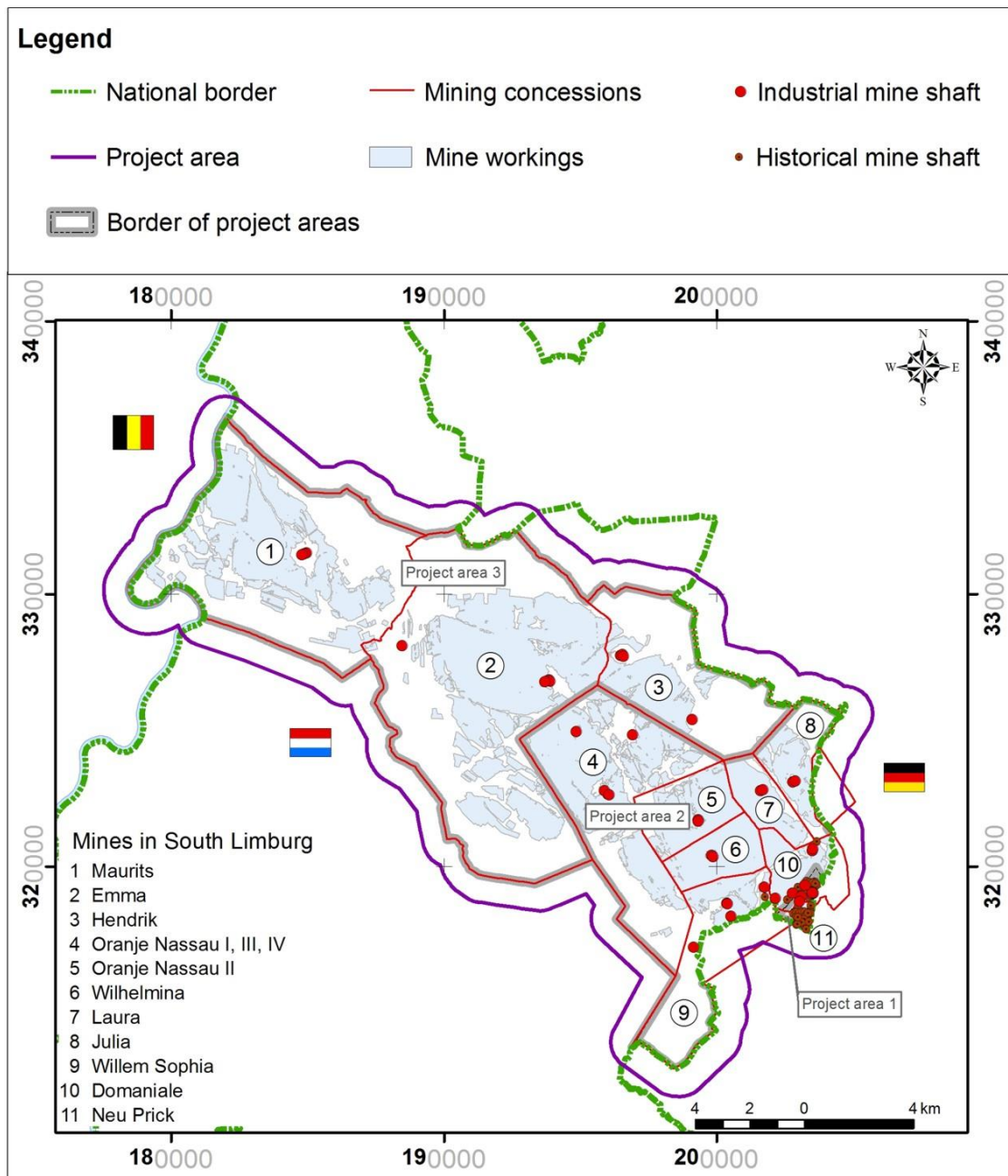


Fig. 13: Mining relicts in the South Limburg mining district

At the beginning of industrial mining, mining regulations allowed for mining only below a thick crown pillar height. Since 1939, however, mining regulations allowed the mining companies to reduce crown pillar heights from 50 m to 10 m or even 3 m. The coal seams that were mined below a crown pillar height of less than 20 m are defined as “industrial near-surface mining” in this project.

In the era of industrial mining, each mine was in general equipped with 2 to 4 shafts. Most of these shafts have already been backfilled; the majority of deep “industrial” mine shafts were abandoned in the 1960s and 1970s in accordance with the guideline “Nadere regelen Mijnreglement vullen van schachten” (MINISTERIE VAN ECONOMISCHE ZAKEN, 1973).

Today, five former shafts have been equipped with pipes for monitoring the mine water level (Fig. 6).

In this research project, the South Limburg mining district was subdivided into three project areas in order to be able to consider the different geologic-tectonic conditions, as well as the different mining situations (e.g. folded coal seams vs. flat dipping coal seams; thin overburden vs. thick overburden; historical near-surface mining vs. mining using more advanced techniques) that were mentioned above. In general, “historical” near-surface mining took place in the southeastern part of the mining district (within the Domaniale and Neu Prick concessions), whereas “industrial” mining took place in the southeastern part, as well as in the centre and in the northwestern part of the South Limburg mining district (Fig. 13).

4 Assessment of the after-effects from mining in South Limburg - results of the working groups

The evaluations are documented in the final report of each separate working group (working groups - “WG”: WG 5.2.1 / WG 5.2.2 and WG 5.2.3 / WG 5.2.4 and WG 5.2.5 / WG 5.2.6 / WG 5.2.7 as shown in Fig. 1). These reports include a detailed documentation of the evaluations, as well as the assessments of potential future risks and proposals for monitoring and possible measures based on Bow-Tie-Analyses of the relevant potential hazards (“Top Event”). The main results of the individual final reports are summarised below. On the basis of the individual final reports an integrated Bow-Tie-Analysis has been made.

4.1 Ground movements (WG 5.2.1)

4.1.1 Approach

After the abandonment of the coal mines in South Limburg in the 1960s and 1970s, significant ground heave has been observed. This has been induced by rising mine water. Taking the progression of the rise of mine water until now into consideration, it may be assumed that mine water is still going to rise over a long period of time (at least 15 to 20 years) before a stable hydraulic equilibrium is reached (see Section 5). Owing to the ongoing rise of mine water, further ground heave has to be expected. In this research project, WG 5.2.1 had to give an answer to the question: What impacts, related to ground heave and affecting the ground surface, have to be expected in the future?

An evaluation of the available information of ground movements was carried out by using levelling data, GNSS (Global Navigation Satellite System) data, and satellite data (InSAR). In particular, Persistent Scatterer Interferometry (PSI)

analyses were applied to the satellite data sets which have been available since 1992.

An important part of the processing of data was the integration of levelling data and satellite data. This has provided more detailed information for the visualisation of the development of ground movements in South Limburg since 1974. The levelling and satellite data sets have been converted to various ground movement products, such as maps, profiles, and time series for representative benchmarks. The evaluation of the geodetic data (levelling and satellite data) available for the mining area of South Limburg for the period 1974 to 2014 provides a detailed picture of the temporal and spatial development of ground movements within the project area. With this information, ground movements induced by rising mine water in the past could be analysed. These data and analyses are the basis of the prediction of future ground heave.

After this step, the way to model ground movements in order to predict future ground movements is discussed and a „prognosis-tool“ is presented and tested for representative key points. Based on the evaluation of the ground movements that have taken place until now, and on the prognosis of further ground heave, potential impact areas with a potential risk of damage to buildings in the future have been defined. Damage may be expected in areas with sudden differences in the development of ground heave (discontinuities) or in areas with high gradients of ground heave. The risk factors that might lead to the development of discontinuities in zones of differential ground heave are described and the impact potential is estimated.

Based on a Bow-Tie-Analysis of the Threats and Consequences that might lead to or arise from differential ground heave, preventive measures and a monitoring concept are presented.

4.1.2 Spatial and temporal development of ground movements

An outline of the ground movements that have been detected in the South Limburg mining district since 1974 is given in Fig. 14. The centres of ground heave are situated in the areas of extensive mining in the concessions of the Maurits, Emma, Hendrik and Oranje Nassau III, IV coal mines at Geleen, Stein, and Brunssum. In these areas, ground heave has attained maximum amounts of 300 to 350 mm until now. Mine workings are already completely flooded in these areas, and in the overburden groundwater levels have already risen as well. Consequently, a decompaction of the overburden layers has to be expected in these areas, too, which contributes an important proportion of the total ground heave.

Within the Julia concession, considerable values of ground heave have also been detected, of approximately 150 to 200 mm. Here, the overburden is already involved in changes of groundwater levels. Consequently, an additional decompaction of the overburden layers has to be expected here too.

In the southeastern coal mines of South Limburg (Wilhelmina, Willem Sophia and Domaniale), significantly smaller amounts of ground heave have been observed; the maximum heave amounts to around 100 to 150 mm. In contrast to the situation in the central and northwestern mining regions, in the southeastern area no significant contribution from decompaction of the overburden has to be expected as no significant changes of groundwater levels in the overburden have occurred here until now.

The areas of ground heave are significantly divided by the SW-NE-striking anticlines of Puth and Waubach, as well as by the Willem fault (see Fig. 7). Due to minor mining activities along these lines, ground heave is decreasing gradually in these areas. Hence, there is a spatial tripartition of the areas of ground heave (see Fig. 14).

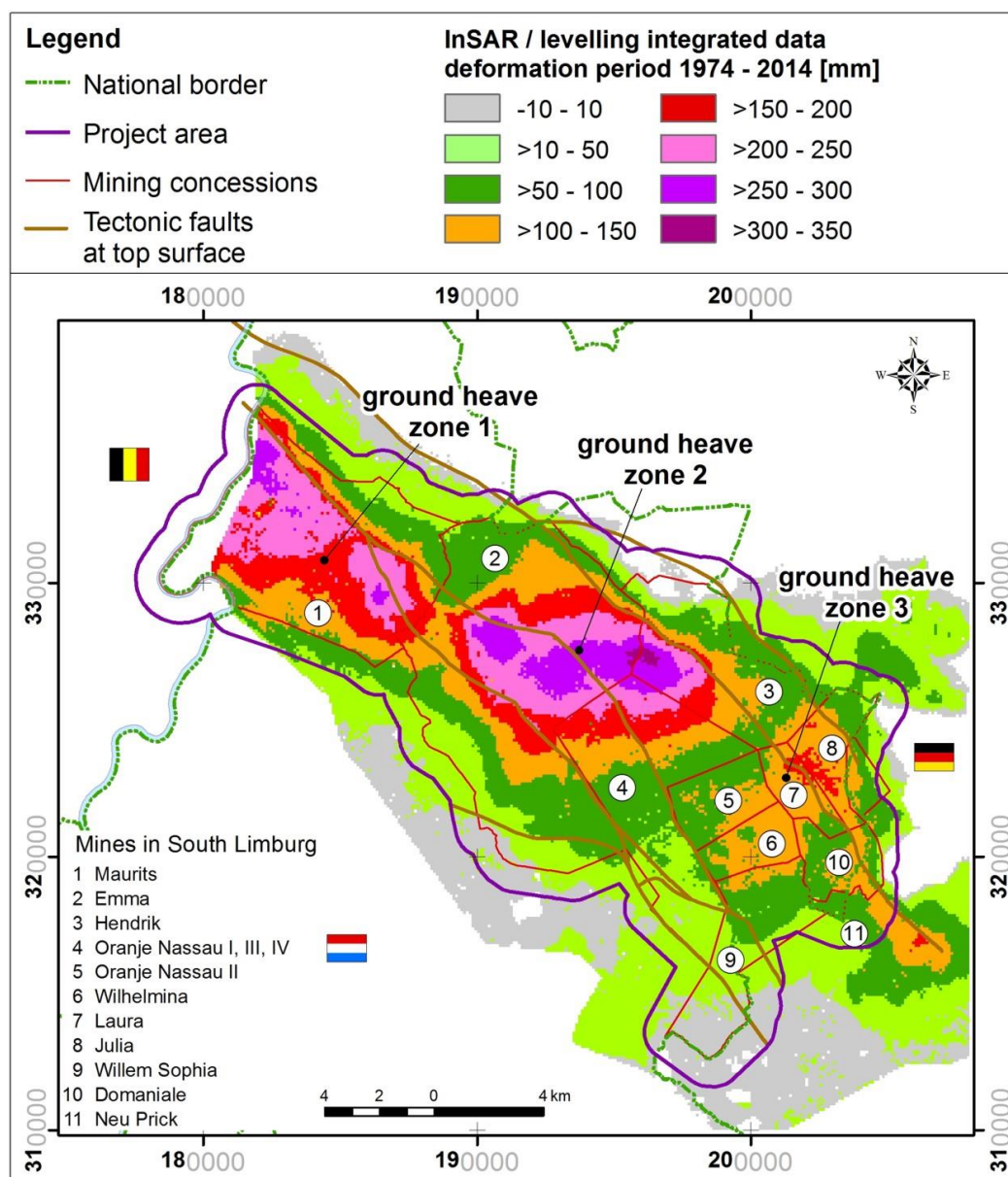


Fig. 14: Ground movements in the South Limburg mining district from the beginning of mine closure in the 1970s, for the period 1974 - 2014

Overall, the areas that have been characterised by significant ground heave since 1974 (of more than 10 mm) are mainly limited to the envelope of the mine workings and their immediate surroundings. In the border region between the South Limburg and the Aachen mining district, additional ground heave is taking place

that is induced by the flooding of the German coal mines. In the border region between the South Limburg and the Belgian mining district (the Eisden mine) additional ground heave resulting from the flooding of the Eisden mine has been taking place since the end of the 1980s, after the Eisden mine was closed.

With regard to the potential damage induced by ground heave, it is not the ground heave spread over a wide area which is important, but those locations where ground heave may develop unsteadily, with higher gradients of even sudden, steplike changes (discontinuities).

Considering the spatial distribution of significant gradients in the development of ground heave, the following areas are most important:

- the northeastern edge of the mine workings of the Maurits coal mine in Geleen, along the Heerlerheide fault - the northeastern margin of ground heave zone 1;
- the northeastern edge of mine workings of the Emma and Hendrik coal mines in Brunssum, along the Feldbiß fault zone - the northeastern margin of ground heave zone 2.

Apart from these areas with higher gradients of ground heave, in the remainder of the mining district, changes in ground heave are developing over a wider area but with significantly smaller gradients.

The development over time of ground movements in the various basins of the South Limburg mining district is depicted by individual representative graphs of the time-deformation-development in Fig. 15; the depicted deformations refer to a reference measurement that was carried out in 2012. In principle, the development of ground heave over time is determined by the progress of the rise of mine water, which includes the three phases that were discussed in Subsection 3.1.

In the first phase until about 1985, major movements occurred in the northwestern basins 1, 2, 3 and 5 (the concessions of Maurits, Emma, Oranje Nassau I, Oranje Nassau III and Oranje Nassau IV).

In the second phase between 1986 and 1994, a temporary slowing down of the ground heave became apparent in most of the basins due to a temporary stabilisation of the mine water level. In contrast to the other basins, in basin 1 (Maurits) ground heave in the second phase seemed to continue at more or less the same rate compared with the first phase.

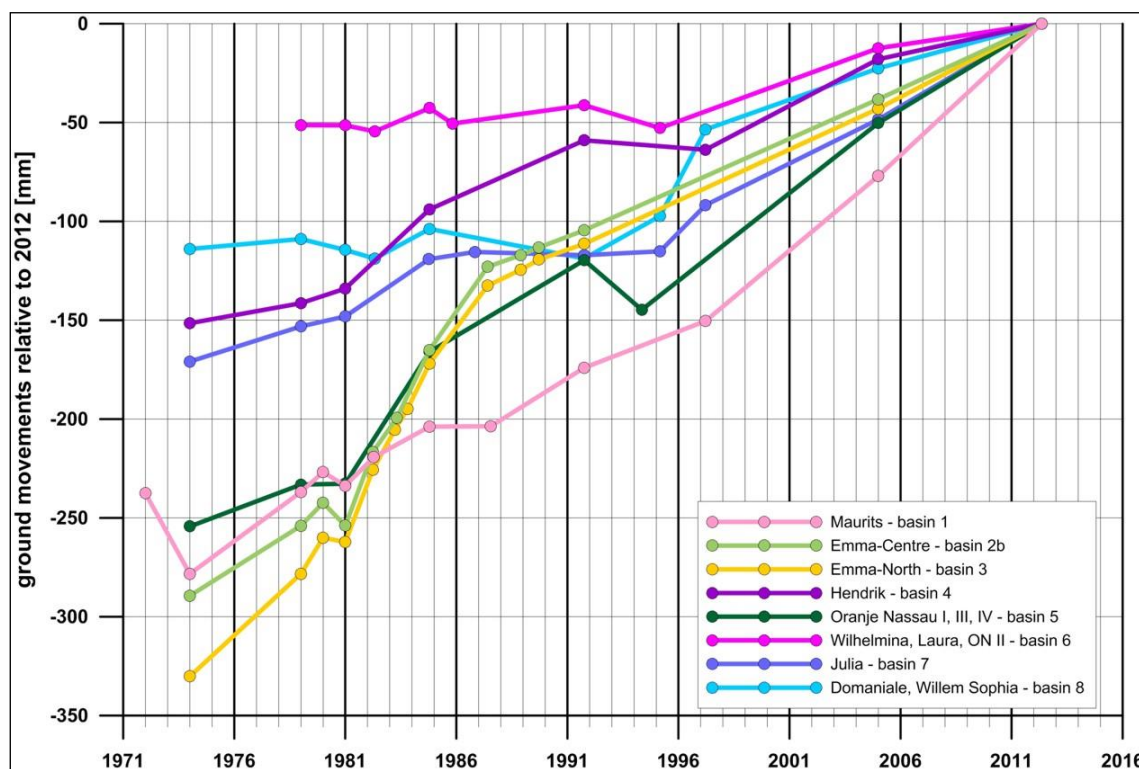


Fig. 15: Development of the ground movements in the different basins of the South Limburg mining district since the 1970s (see Fig. 4 for the location of basins)

This might be attributable to the fact that, within basin 1 (Maurits), the rise of mine water is proceeding independently from the other basins within South Limburg. This may be due to an additional influence from the rise of mine water in the Belgian Eisdan mine.

In the third phase, ground heave increased again, but the rate of the mine water rise decreased significantly. Mine water rises homogeneously within all basins now (with the exception of basin 1, the basin of the Maurits coal mine). The recent development of ground heave (starting in 2009) is illustrated in Fig. 16.

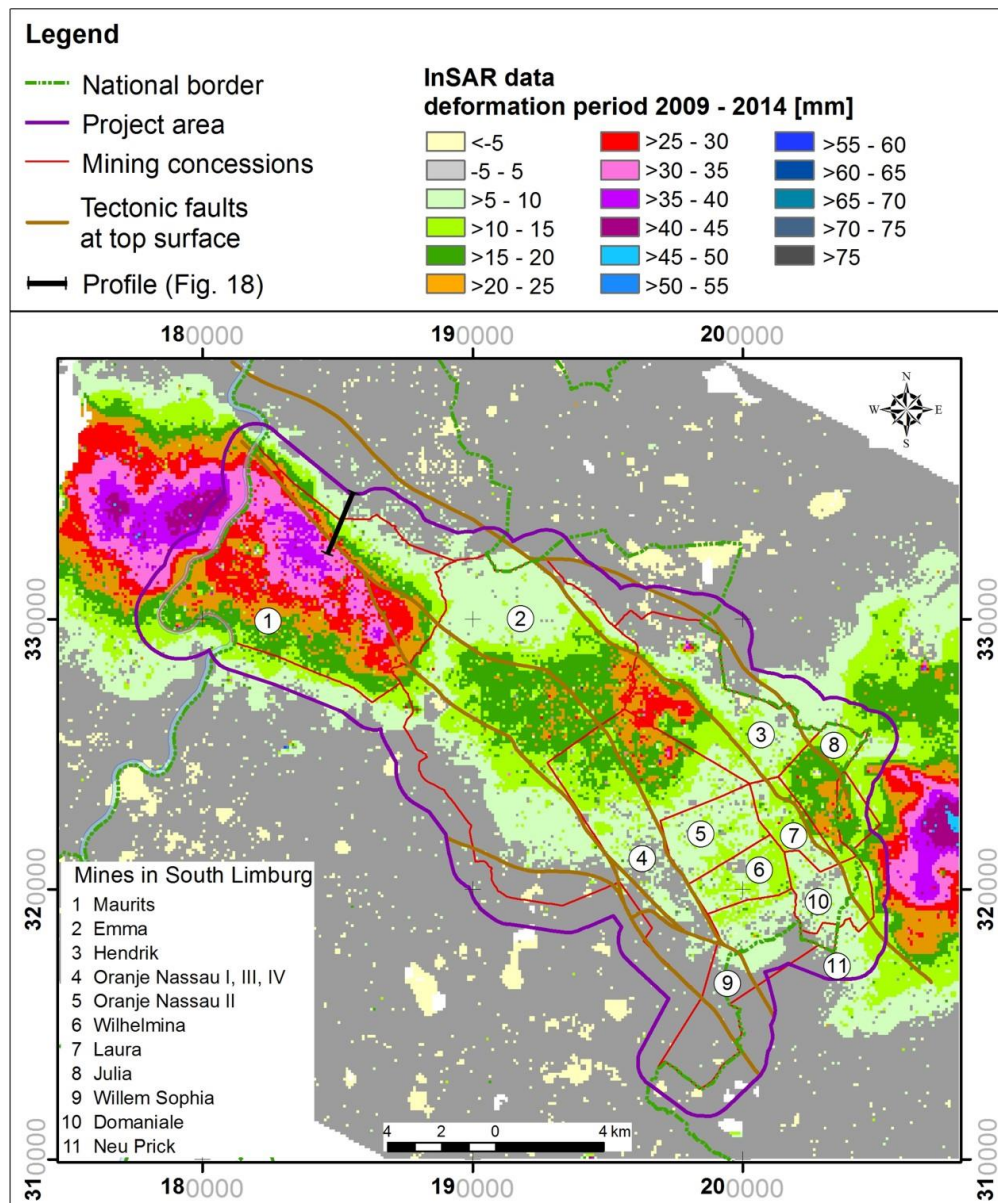


Fig. 16: Spatial distribution of ground heave in the South Limburg mining district - for the period 2009 to 2014, with a cross-profile according to Fig. 18 (see the black line in the Maurits mine)

In the southeastern ground heave zone 3, only minor amounts of ground heave (less than 15 mm) could be observed in the period 2009 to 2014. Only in the area of the Julia coal mine did a more significant ground heave (with a maximum of 25 mm) take place due to the additional impact of decompaction in the overburden layers. Within zone 2, ground heave continued and increased by about 10 to 20 mm.

The maximum ground heave in the Brunssum area near the Feldbiß fault zone is about 25 to 30 mm for the period between 2009 and 2014. The most marked ground heave is still taking place within the northwestern zone of ground heave zone 1 (Maurits). Between 2009 and 2014 maximum ground heave values of approximately 35 to 40 mm were detected here. Approaching the border region between the Maurits and the Belgian Eisden coal mine, the values of ground heave increased up to between 40 and 45 mm in the Belgian territory during the period 2009 to 2014.

4.1.3 Prognosis of future ground heave

An important objective of the research project was to develop a method for predicting (differential) ground heave due to the rise of mine water. In principle, ground heave resulting from mine water rise is a consequence of the decompaction of the broken coal-bearing bedrock due to increased pore water pressure.

A first approach to the calculation of ground heave was presented by PÖTTGENS in 1985. For the determination of ground heave values, the strain- or decompaction-coefficient of the flooded bedrock is an essential factor. To account for the conditions in the South Limburg mining district, PÖTTGENS used a medium value of $3,5 \cdot 10^{-9} \text{ m}^2/\text{N}$. The present study has reproduced this approach and has shown it to be plausible. The decompaction coefficient proved to be $2,5 \cdot 10^{-9}$ to

$3,5 \cdot 10^{-9} \text{ m}^2/\text{N}$, assuming a thickness of the zone of disturbed rock of 4 times the coal seam thickness.

The resulting ground heave of a specific reference point at the ground surface is determined, depending on the respective mining situation, by the decompaction of the mine workings at different depths and distances to the reference point which have different proportions in the overall ground heave at the reference point. The strongest impact is attributed to those mine workings that are situated directly below the reference point. The impact decreases with increasing distance and depth. The proportion of the different mine workings in the overall ground heave of a reference point is determined by an influence function. Within the present study, the influence function of GEERTSMA (1973) is applied. This function was also used by PÖTTGENS (1985) and is, furthermore, used for the prognosis of subsidence due to gas extraction in the area of the gas fields around Groningen.

Due to the considerable computational complexity, the calculations of ground heave were not performed for the whole area, but only for some representative benchmarks. The ground heave resulting from the flooding of the coal-bearing bedrock can, however, be reconstructed very well with these calculations (Fig. 17).

Once mine water has reached the basal overburden and, therefore, leads to a rising groundwater level in the overburden sediments, as would be expected, ground heave values are underestimated by the chosen approach because the calculations only consider the amount of ground heave that results from strain from the coal-bearing bedrock. At this point, additional decompaction of the overburden layers resulting from rising groundwater levels has to be considered in the calculations.

Hence, for the estimation of the ground heave induced by decompacted sediments of the overburden, an empirical approach was chosen. It was found that ground heave due to decompaction of the sediment cover is linearly related to the change in mine water level. So, for each key point, the relevant coefficient that describes the linearity between rising mine water head and ground heave was determined from the already available data about ground movements and rising mine water level. This approach makes it possible to make a prognosis of future ground heave, for a given mine water level, quickly and efficiently for each surface point, where the sediment cover is flooded.

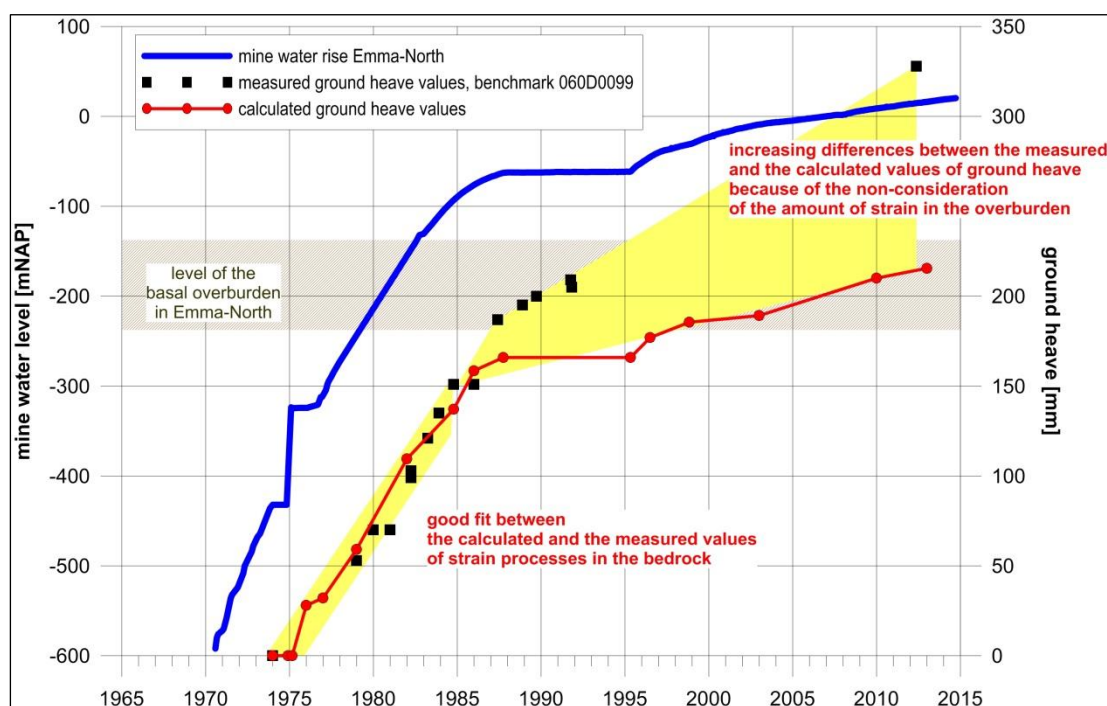


Fig. 17: Comparison between the measured and the calculated values of ground heave at benchmark 060D0099, Emma coal mine

With this approach, a prognosis for future ground heave is given based on the calculations for representative key points. The overall ground heave potential has been estimated to reach a maximum of 440 to 500 mm based on the current prognosis for the centre of ground heave in ground heave zone 2. The major part

of ground heave has already taken place, but in the future, a further ground heave of about 110 to 170 mm maximum is to be expected.

Within the present study, a prognosis tool for the estimation of ground heave resulting from the rise of mine water was developed; this tool needs further empirical verification. In addition, one has to determine to what extent differences in ground heave at hydraulically effective fault zones can be estimated by this approach. This study gives the initial impetus to the tool, but further research is still necessary.

4.1.4 Assessment of impact potential

As a basis for the assessment of the potential risk arising from ground heave due to rising mine water, a three-level classification was devised for the German coal mining districts. This classification provides three impact categories with different probabilities of the occurrence of damage-relevant differential ground heave or discontinuities (HEITFELD et al., 2015). The categories are as follows:

- **Impact category EK 1 (“red zone”)** -
high probability of the occurrence of significant differences in ground heave and the development of discontinuities.
- **Impact category EK 2 (“yellow zone”)** -
medium probability of the occurrence of significant differences in ground heave and the development of discontinuities.
- **Impact category EK 3 (“blue zone”)** -
low probability of the occurrence of significant differences in ground heave and the development of discontinuities.

The application of these criteria allows for both the definition of possible zones of discontinuity related to the rise of mine water and the differentiation with respect to the probability of occurrence.

A fundamental risk factor is the existence of a main tectonic fault zone, which may act as a predominant movement path for potential differential ground movements on the boundary of mine workings. Along such a tectonic fault zone, differential development of mine water/groundwater levels in the Carboniferous rock, as well as in the overburden on both sides of the fault, might produce differential ground movements.

The assignment of possible zones of discontinuity to one of the impact categories is based on the existence of such a main tectonic fault and on further basic risk factors such as rise of groundwater levels in the overburden, the existence of “Drempels” from active mining along the fault zone or actual damage to buildings or infrastructure in that area. Taking these risk factors in consideration, the mining areas along the Heerlerheide fault in Geleen and along the Feldbiß fault zone in the Brunssum and Eygelshoven have been identified as zones where the development of significant differential ground heave due to the rise of mine water in the future cannot be excluded. Data of the previous development of ground movements confirm that these are the areas where the steepest gradients have developed until now.

In order to assign impact categories to areas, the local geological and hydrogeological conditions, as well as the mining conditions, were appraised as a first step. Subsequently, as a second step, the positive experience gained from the evaluation of the previous ground heave was included. Thereby, it has to be taken into consideration that the rise of mine water has already advanced to a considerable extent: the biggest part of the ground heave has already evolved. Until now,

the potential impact zones have shown a gradual decrease of ground heave without significant discontinuities.

According to the above-mentioned procedure, the assessment of potential impact areas is as follows (see Plan 1):

- **Potential impact area 1** (impact category EK 2, “yellow zone”) at the Heerlerheide fault in the Geleen area
- **Potential impact area 2** (impact category EK 3, “blue zone”) at the Feldbiß fault in the Brunssum area
- **Potential impact area 3** (impact category EK 3, “blue zone”) at the Feldbiß fault in the Eyselshoven area

The development of ground movements along such a tectonic zone is shown by a representative cross-profile in the form of a time-deformation-diagram, as shown in Fig. 18 (based on InSAR data); the locations of the cross-section are depicted in Fig. 16. The cross-section depicts the relative development of ground heave according to the 1992 measurement. Thus, the diagrams represent the ground heave that has developed during the last phase of the rise of mine water.

Fig. 18, which shows the cross-section across the Heerlerheide fault, indicates that the amount of ground heave is decreasing gradually from the mined area towards the northeast. Even in the most probable location of the Heerlerheide fault, there are no indications of the development of a significant discontinuity. This indicates that the Heerlerheide fault (“yellow zone”) has not yet been activated as a major movement path because of ground heave due to the rise of mine water. The same applies for the areas in impact categories EK 3 (“blue zone”).

According to the present scientific investigations with regard to the occurrence of damage due to differential ground heave, no significant differential ground

heave, which might produce damage to buildings or infrastructure at the ground surface, has to be expected outside the three above-mentioned potential impact zones.

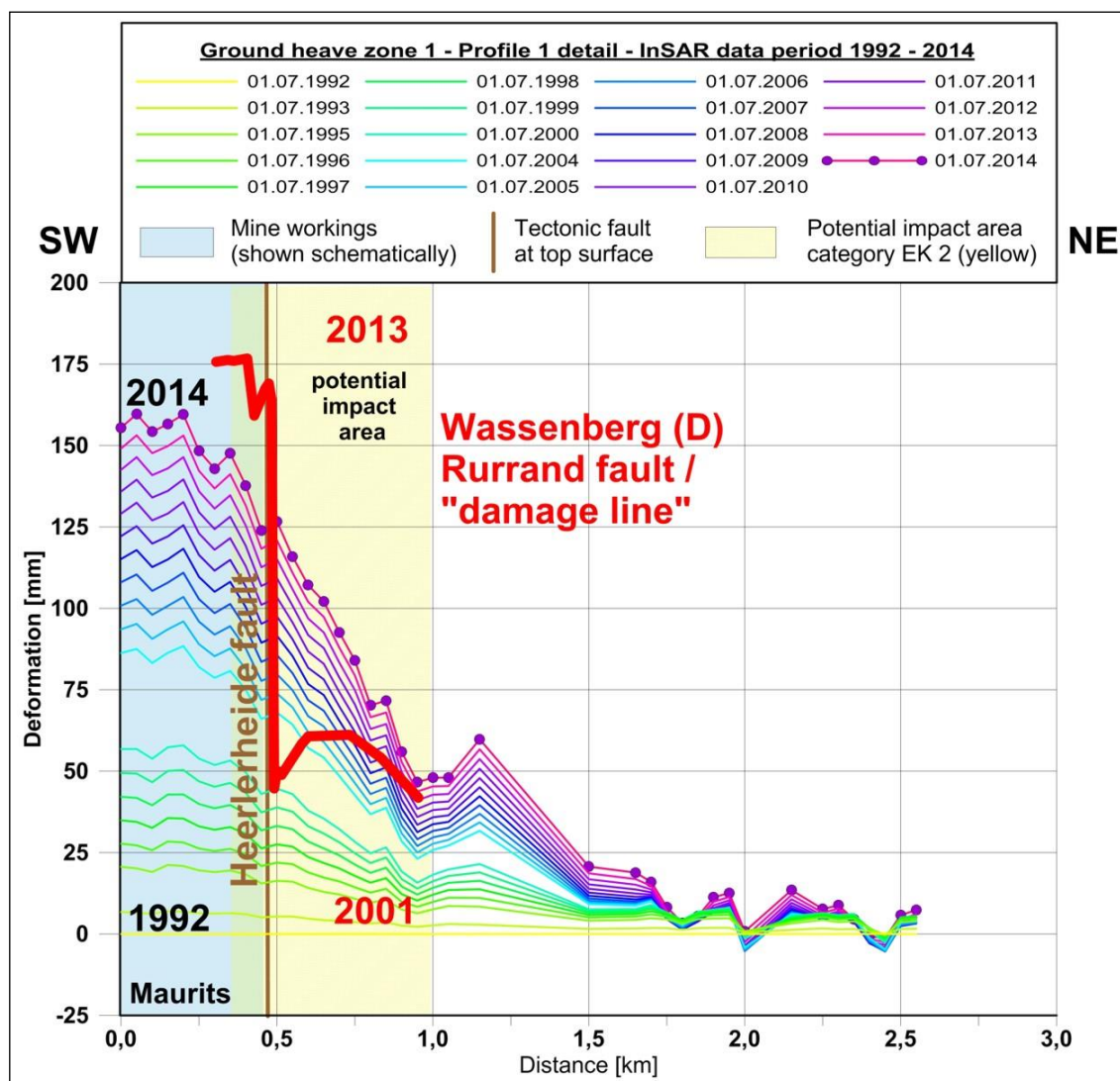


Fig. 18: Comparison of the ground heave gradients at the Heerlerheide fault in the Geleen area (ground heave zone 1) and the Rurrand fault in the Wassenberg area, Germany

With regard to the assessment of the future damage potential due to differential ground heave, it has to be stated that, first of all, ground movements induced by the rise of mine water constitute only a fraction of the primary effects of mining-

induced ground movements (up to 10 m of subsidence due to coal extraction by active mining). Therefore, in principle, the damage potential of ground heave induced by the rise of mine water is several magnitudes smaller.

In other flooding areas of coal mining (e.g. in North Rhine-Westphalia), to date, no serious damage has been detected in potential impact zones assigned to impact categories EK 2 and EK 3. The only heavy damage has been observed at the Rurrand fault in the Erkelenz mining district (city of Wassenberg, Germany). The situation in Wassenberg represents impact category EK 1, where a distinct discontinuity with a vertical ground displacement of more than 100 mm developed within a very short distance of less than 10 m within a period of approximately 12 years (see Fig. 18). The situation of impact category EK 1 differs very much from the situation in the potential impact areas EK 2 and EK 3 assigned to the three areas in South Limburg.

Hence, in principle, the risk of damage caused by the remaining rise of mine water in South Limburg is quite low. Nevertheless, impacts to buildings and/or infrastructure cannot be entirely excluded. Serious damage (in the sense of a „constructive total loss“) is not expected.

This statement about the risk of damage follows the relevant criteria for the assessment of damage to buildings. Special structures or sensitive infrastructure with special requirements concerning their positional stability have to be estimated on a case-by-case basis.

4.1.5 Bow-Tie-Analysis and monitoring plan

In terms of Bow-Tie-Analysis, differential ground movements are considered as the Top Event which might be induced by the rise of mine water in areas with

specific geological and mining conditions (three potential impact areas along the main tectonic faults). The Bow-Tie-diagram is shown in Appendix 1.

A further risk factor with respect to differential ground movements is the different development of the groundwater level in the overburden on the two sides of such a main tectonic fault. Such a different development of groundwater levels in the overburden cannot be induced only by the rise of mine water, but also by groundwater extraction.

If differences in ground movements occur over a very small distance, differential ground movements can damage buildings or sensitive infrastructure (e.g. pipelines). Also, the functionality of infrastructure can be influenced by changes in the inclination of infrastructure (e.g. sewers). Finally, the potential for the development of damaging differential ground movements can cause social unrest in the affected areas. People are afraid that their houses will be damaged and may not be able to assess the actual risk realistically.

In practice, this possible Threat can only be mitigated by preventing a further rise of mine water by starting to pump out mine water again. However, such an extensive and perpetual measure is not proportional to the risk potential. The pros and cons of this measure are discussed in detail in Section 5. The main appropriate prevention control is the monitoring of the factors that may lead to differential ground movements. These are the levels of mine water, the levels of groundwater in the overburden, and ground movements. By monitoring these factors, risk zones may be identified early enough and precisely enough to start appropriate recovery measures. Furthermore, these monitoring measures are necessary to build an information basis for the assessment of damage at the surface, and the identification of the rise of mine water as the possible cause of damage at the surface.



For a better understanding of the processes in the underground of the three potential impact areas and a better base for the assessment of the actual risk, a pilot project in the potential “yellow” impact area of Geleen is proposed. The pilot should provide specific information on the characteristics of the tectonic shear zones along main faults near to the surface. For the risk assessment, it is very important to establish whether a single predominant movement path is developing along the fault zone, or whether several paths with a distance of some metres is developing.

The risk that serious damage occurs to existing buildings is low. Therefore, preventive measures are not required for existing buildings. However, with respect to new building projects and new sensitive infrastructure facilities within the potential “yellow” and “blue” impact areas, some preventive measures are recommended. These measures can prevent damage in case significant differential ground movements occur. It would be advisable to review sensitive infrastructure facilities, and to take into consideration the potential development of differential movements when planning buildings, pipelines, and/or infrastructure.

Important instruments to prevent social unrest in case of the occurrence of differential ground heave or small damage of buildings are awareness-raising and communication. People should be informed about the situation, and should get an explanation of the things that happen underground, the probability of damage, and the measures that are available to protect or repair their property. People should also know whom they can contact in case of damage, and who will be responsible for repairing the damage.

When damage to buildings or infrastructure occurs, immediate measures such as detailed monitoring of the damage and a structural analysis of the affected building or infrastructure have to be initiated. If necessary, constructional support work should be carried out to prevent further damage, and damage that has al-



ready occurred might be repaired. With these measures, a total loss of buildings or infrastructure can be prevented, and the usability restored.

To conclude, the probability that damage occurs due to differential ground movements is, in general, low. There are measures to prevent severe damage in case damage occurs. The main instrument to handle this after-effect is to monitor the ground movements themselves, as well as other inducing factors such as the rise of mine water and the change of groundwater levels in the overburden.

For the monitoring programme, it is necessary to initiate a supplementary programme based on terrestrial measurements (e.g. levelling, GNSS) as a reference, on the one hand, and on satellite measurements on the other, as these deliver a higher density of measurement points and provide an efficient possibility to have a higher rate of measurement. As an absolute reference for the evaluation of the InSAR data, an adequate net of GNSS-stations is needed in the region. With the different use and combination of both methods, the accuracy of the resulting data will differ. A higher accuracy is needed if, for instance, there are discussions about the interpretation of the measured ground movements, or if damage occurs that is not understood. Therefore, the proposed monitoring plan consists of a stepwise scheme which differentiates between measures of first-, second- and third-order priority. The details are discussed within the integrated Bow-Tie-Analysis (see Section 6).



4.2 Mine shafts (WG 5.2.2)

4.2.1 General approach

In general, abandoned mine shafts are regarded as a potential problem for ground stability in affected areas. A failure of a shaft might cause subsidence or a sink-hole. Within the context of this study, a distinction has been made between shallow “historical” mine shafts and deep “industrial” mine shafts.

From the present-day perspective, the general safety level of both the shallow “historical” mine shafts and the deep “industrial” mine shafts has to be questioned and checked.

An assessment of the safety level of each known shaft was undertaken based on the evaluation of all available documents. In addition, the most probable position of all “historical” mine shafts was determined.

The assessment of the safety levels was performed following the procedure that is used in Germany, in the North Rhine-Westphalian mining district. This procedure is based on the concept of what are called “Shaft-Protection-Zones”. To be able to assign a precise safety level to a shaft, four different “impact categories” have been devised. Those are assigned to the individual “Shaft-Protection-Zones” of the shafts.

A Bow-Tie-Analysis was performed for the “geotechnical hazard” of abandoned mine shafts. For “historical” mine shafts, a prioritisation system, together with an On-Site-Investigation-Programme, and a Remediation-Programme is recommended. For “industrial” mine shafts individual measures were proposed.

4.2.2 Data basis and definition of “Shaft-Protection-Zones”

The present study is based on approximately 7.700 georeferenced mining maps and profiles, as well as on numerous documents about the abandonment of mine shafts that were gathered prior to the study. In general, there was no information on the abandonment of the “historical” mine shafts, while the information on the abandonment of the “industrial” mine shafts was more or less complete. The location of all mine shafts can be seen in Plan 2.

With regard to the “historical” shafts, there already was a compiled list of 56 known “historical” shafts within the Domaniale and Neu Prick concessions. The data was digitised and correlated with the mining maps. Three additional “historical” mine shafts were revealed by a detailed evaluation of the historical mining maps. A data set was created for each of the “historical” mine shafts that include all available data.

In accordance with the procedure that is applied in the North Rhine-Westphalian mining districts, “Shaft-Protection-Zones” (i.e. the area that is potentially affected owing to failure of a shaft) were assigned to the shafts, considering the dimension of the shaft, a safety margin, a width resulting from the impact of the overburden, and the accuracy of position. The evaluation revealed that further “Shaft-Protection-Zones” of six “Historical Shafts”, situated across the German border, extend into the Netherlands.

The positions of all 39 “industrial” mine shafts are well documented. The data was digitised; and the data set for each shaft was enhanced with additional basic information about the shafts.

In a second step, the available documents and reports were evaluated in detail with regard to the applied stabilisation measures for abandoning the shaft. Sub-

sequently, “Shaft-Protection-Zones” were assigned to all “industrial” mine shafts.

4.2.3 Definition of impact categories for risk assessment

In accordance with the approach that is applied in the North Rhine-Westphalian mining districts, four categories (“impact categories”, “EK”) were distinguished in the risk assessment of mine shafts. All categories describe the relative probability of the occurrence of a collapse, sinkhole, or subsidence (see Tab. 1). It has to be emphasised that the relative ranking terms of “high”, “medium” and “low” have to be interpreted in the context of a low absolute probability.

Following the procedure that is applied in North Rhine-Westphalia, all “historical” shafts (and their respective “Shaft-Protection-Zones”) were assigned to impact category EK 1 (“red”).

This was done because, in general, the probability that a collapse, sinkhole, and/or subsidence occurs, resulting from failure of a “historical” shaft, is increasing over time (“risk is active and increasing in time”). This is due to degradation and weathering processes and extends to all “historical” shafts. An influence of the rise of the mine water level is not expected, however, as the predicted mine water level (80 mNAP in the “average case”) is below the bottom or lowest point of most “historical” shafts.

To refine the assessment of the 59 “historical” shafts, as well as to set up a prioritisation system for handling the shafts, on-site inspections were undertaken to collect further information on land use in the defined “Shaft-Protection-Zones”.



Tab. 1: Definition of impact categories and outcomes of the assessment of the industrial mine shafts

Impact category (colour)	Relative probability of occurrence ¹⁾	Shaft	Mine	Safety level
1 (red)	High	-	-	-
2 (yellow)	Medium	Buizenschacht, Willem I/II Beerenbosch I Neuland Melanie	Domaniale Willem Sophia	Very low or not yet treated
3 (blue)	Low	Baamstraat Louise Catharina Willem I/II Sophia Laura I/II Julia I/II all 7 shafts Shafts I/II Shafts I - IV Shafts I - IV Shafts I - III	Domaniale Neu Prick Willem Sophia Laura-Julia Oranje Nassau Wilhelmina Emma Hendrik Maurits	Low or medium safety level
4 (green)	None	Beerenbosch II Nulland HAM II	Domaniale Willem Sophia	Permanently safe or high safety level

1) The relative ranking terms have to be interpreted in the context of a low absolute probability of occurrence.

Since all the “Shaft-Protection-Zones” are located within the urbanised area of Kerkrade (former concessions of “Domaniale” and “Neu Prick”), the shafts were classified on the basis of the vulnerability of the specific land use in three categories with decreasing potential for vulnerability:

- Category 1: Shafts in areas with “goods deserving/requiring **high** protection” (Under buildings or very close to buildings);



- Category 2: Shafts in areas with “goods deserving/requiring **medium** protection”
(Near buildings, in gardens or streets, etc.);
- Category 3: Shafts in areas with “goods deserving/requiring **low** protection”
(Forests, grassland, etc.).

Since the “historical” shafts are considered to have a high relative probability¹ for potential failure, the initiation of certain actions for mitigation is recommended. The recommendations are given below.

With regard to the “industrial” shafts, the availability of data allowed for a rather detailed assessment of the impact categories. On the basis of various criteria, such as sealing type, grip length of the sealing plug, and taking the current regulations in North Rhine-Westphalia on the abandonment of mine shafts as benchmarks, the assessment of the 39 “industrial” shafts yielded the following results (Tab. 1, Plan 2):

- three “industrial” shafts are “permanently safe” or have a “high safety level” (Category EK4, “green”);
- 30 “industrial” shafts have a “medium” or “low safety level” (Category EK 3, “blue”);
- six “industrial” shafts have a “very low safety level”, or are even “not yet treated” (Category EK 2, “yellow”).

The respective impact areas of the shafts are shown in Plan 2.

¹ The relative ranking terms have to be interpreted in the context of a low absolute probability of occurrence.



In general, the probability of occurrence of collapse, sinkhole, and/or subsidence resulting from the failure of an “industrial” shaft is increasing over time (“risk is active and increasing in time”). In addition to degradation and weathering processes, the rising mine water level is regarded as having a destabilising effect.

4.2.4 Bow-Tie-Analysis and recommendations for handling the risk from mine shafts

In the Bow-Tie-Analysis for mine shafts, the potential occurrence of collapse, sinkhole, and subsidence is defined as Top Event; Threats that might trigger the Top Event are mainly related to the failure of specific parts of the shaft, including the shaft head, deep closure structures, and sealing plugs, the backfill column, and the shaft lining. Additional Threats are related to specific geological conditions. The respective Bow-Tie-diagram is depicted in Appendix 1.

In the case of a Top Event, the Consequences are limited to the defined “Shaft-Protection-Zones”. The Consequences include injuries or loss of life, damage of certain structures (buildings and infrastructure in particular), as well as social unrest.

The Threats can be prevented by several Controls. For some individual Threats, limitation of loads on the shaft head or in the vicinity of the shaft can be regarded as sufficient measures. As contact with water can have destabilising effects, the limitation of seepage water influx is regarded to be a useful Control for any Threat.

For the “historical” mine shafts, site inspections and remediation measures are necessary Prevention Controls and therefore strongly recommended, whereas safeguarding measures (f.e. barrier and signage of the hazardous area) are con-

sidered as transitional measures that can be taken prior to remediation measures. In general, monitoring measures are recommended for all “industrial” shafts. Remediation measures are required for six “industrial” shafts.

The basic approach to limit the severity of a Top Event (Recovery Controls) is to prevent an increase of the risk by inappropriate construction measures within “Shaft-Protection-Zones”. Therefore, an adapted regional planning is strongly recommended. In addition to this measure, the general public should be informed about potential hazards and risks. Their awareness should be raised. Within impact areas, it is advised that, prior to new construction projects, an adapted site investigation is conducted. Based on the site investigation, it is possible that a construction needs to be adapted in order to meet certain static requirements. In the case of a Top Event, there should be a quick response team that is trained to launch immediate measures. In certain cases, constructional support work is required to further ensure structural stability. If there is no Recovery Control feasible, change of use of an existing construction is regarded as a last option.

It is quite obvious that a collapse or sinkhole on a vertical shaft is a severe incident that will lead to damage to nearby buildings. If people are present, the incident might even cause injuries or loss of life. As the risk of severe damage is high, and the impact areas are quite well-defined, the main future target should be to eliminate existing risks in a long-term project, and to prevent the creation of new risks.

Obviously, the treatment of 59 “historical” shafts will be a long-term project; hence, it is recommended to establish an On-Site-Investigation-Programme first, which should result in a graded Remediation-Programme.

The On-Site-Investigation-Programme should be performed in order to verify the actual risk situation and to reduce the “Shaft-Protection-Zones”, starting with

those shafts that are assigned to Category 1. In particular, the results of the On-Site-Investigation-Programme should also be taken into account in order to improve the prioritisation system.

Based on the first results of the On-Site-Investigation-Programme, the Remediation-Programme should be launched as soon as possible.

In parallel with the described programmes, certain administrative tools should be implemented to prevent new risks caused by the construction of new buildings or other changes in land use. Therefore, it is strongly recommended that any project (a construction planning or other development planning) inside “Shaft-Protection-Zones” is forbidden unless an individual solution is defined (“Development Freeze”) for the specific situation.

The graded assessment of the “industrial” shafts allows for specific recommendations for each impact category.

For the shafts that are assigned to EK 4 and EK 3, conducting a monitoring program is considered to be sufficient. The intensity of monitoring should comply with the respective safety level of a shaft. Where necessary, the assessment of the safety level has to be revised based on the results of the monitoring programme.

For the six shafts that are assigned to EK 2, short-term launching of investigation measures is strongly recommended. In a second step, additional remediation measures should be applied. For the shaft that is “not yet treated”, additional access limitations (fencing-off the area) should be implemented.

4.3 Near-surface mining (WG 5.2.3)

4.3.1 General approach

Even a long time after mining activity has ceased in an area, former underground mine workings can affect the stability of the ground surface. Commonly, the mine workings were not backfilled after a coal seam was mined; i.e. the hanging wall rock was allowed to collapse into the mined seam. However, in some cases, the hanging wall rock did not collapse entirely so that there still might be open mine voids underground.

Following the procedure that is applied for risk assessment in the Aachen mining district, what are called “impact areas” are defined for the historical mining area of Kerkrade. For the industrial mining area, “impact areas” are defined using a new approach that is mainly based on the findings of the sinkhole event at “Winkelcentrum ‘t Loon”.

Based on the assessment of the specific conditions of each near-surface coal seam, three different “impact categories” are assigned to the defined “impact areas”.

A Bow-Tie-Analysis is performed for the “geotechnical hazard” of near-surface mining. Further recommendations are given, in particular, for new construction projects.

In addition, further mining relicts (upward drillings, downward drillings, “Drempels” and “Verzakkingen” - see Subsection 4.3.4) are discussed and some recommendations are made.



4.3.2 Definition of impact categories and impact areas for near-surface mining

For elaborating the risk assessment for near-surface mining, the same project areas were used that were already introduced in Subsection 3.3. The investigations are based on approx. 7.700 georeferenced mining maps and profiles.

For assessing the risk of these near-surface mine voids, the same approach was chosen that has already been applied in the adjacent historical mining area of Herzogenrath/Germany.

In a first step, the outcrop lines of all coal seams were constructed from the mine maps. In a second step, a potential impact category was assigned to each segment of the outcrop lines. Basically, the used impact categories are the same as those that are used for assessing the mine shafts. The assignment depends on both the tectonic conditions and the mining situation, taking into account the regional significance of each coal seam (“Main Coal Seam”, “Mineable Coal Seam”), the dip of the coal seam ($< 36^\circ$, $\geq 36^\circ$) and the (often rare) knowledge from mining documents.

Subsequently, a potential impact area at the ground surface was defined for each categorised segment. Each impact area is defined perpendicular to the outcrop line of a coal seam to both the tectonic hanging wall and the laying wall; it comprises four components:

- Outcrop width of the coal seam;
- Impact area at the top of the Carboniferous bedrock (taken from empiric diagrams from the Ruhr-Mining-District in NRW/Germany);
- Width resulting from impact of overburden;



- Accuracy of the system.

In total, the constructed outcrop lines add up to approx. 17 km, with impact areas covering most parts of the densely populated area of Kerkrade. The respective impact areas are shown in Plan 3.

In contrast, in the project areas 2 and 3, most coal seams are found to be shallow dipping and overlain by a considerably thick overburden. These deep-lying coal seams were mined in more recent times using advanced techniques (“industrial mining”). Mining was regulated by several regulations that first allowed for mining up to 20 m below the bedrock surface. However, after 1939, mining regulations allowed for a reduced crown pillar height if certain requirements were met. The stopes close to the Carboniferous bedrock surface were commonly not back-filled. Hence, residual voids have to be expected close to the bedrock surface.

In fact, the sinkhole event at “Winkelcentrum ‘t Loon” in Heerlen that occurred in autumn 2011 revealed that stopes under a reduced crown pillar height, albeit covered under a relatively thick overburden, can cause serious damage, even nowadays. Based on the investigations of the sinkhole in Heerlen, as well as being modelled on the impact areas and impact categories that were applied in the historical mining area of Kerkrade, a modified approach for the risk assessment of mine workings close to the top level of the Carboniferous bedrock was developed.

For the risk assessment, an impact-relevant limit depth of 20 m, measured against the top level of the Carboniferous bedrock, was defined i.e. all stopes that are located in the range between 0 and 20 m below the top of the Carboniferous bedrock are assumed to be able to cause hazards to the ground surface.

The definition of impact categories is based on the approach in NRW/Germany but also took into account the specific geologic-tectonic settings in South Lim-

burg. Furthermore, the investigations of the incident at “Winkelcentrum ‘t Loon” in Heerlen were considered.

In a first step, all mine workings were digitised from the available mine maps. In the next step, all mine workings close to the bedrock surface were filtered from this data set.

Subsequently, the potential impact area at the ground surface was defined for each segment. The impact areas were defined around a segment which comprises two components:

- A safety margin of 10 m;
- A width resulting from impact of the overburden.

A scheme for the definition of impact areas can be seen from Fig. 19.

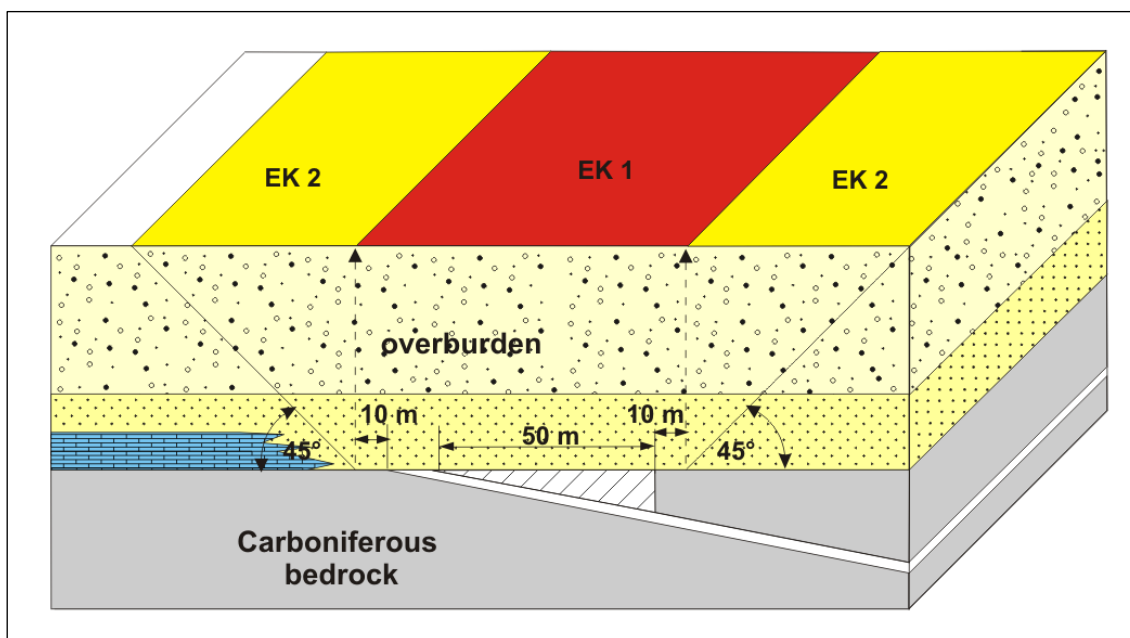


Fig 19: Outline of the definition of impact categories EK 1 and EK 2 in project areas 2 and 3



- Impact category EK 1: area above an acute-angled stope including a safety margin;
- Impact category EK 2: area around Impact category EK 1; width delimited by the impact of the overburden;
- Impact category EK 3: area above and around other stopes between 0 and 20 m below the top of the Carboniferous.

A clustering of impact areas can be found in the southeastern part of the South Limburg mining district. In the northern and northwestern parts, only some scattered impact areas of impact category EK 3 are present. The distribution of impact areas can be seen from Plan 3.

Mine water is considered to have a destabilising effect on crown pillars. Hence, the probability of occurrence of collapse/sinkhole and/or subsidence resulting from failure of near-surface mine voids is increasing along with the rise of mine water.

4.3.3 Bow-Tie-Analysis and recommendations for handling the risks from near-surface mining

In the Bow-Tie-Analysis for near-surface mining, the potential occurrence of collapse, sinkhole, and subsidence is defined as Top Event; Threats that might trigger the Top Event are related to the failure of the rock roof or to the displacement and weakening of (loose) rock material.

In the case of a Top Event, the Consequences are limited to the defined “impact areas”. The Consequences include injuries or loss of life, damage to certain structures (buildings and infrastructure in particular), and also social unrest.

For preventing a Top Event, stabilisation of the underground mine voids and the rock roof is considered to be the only feasible Prevention Control. Nevertheless, there are several Recovery Controls for mitigation. The basic approach for limiting the severity of a Top Event (Recovery Controls) is not to increase the risk by inappropriate construction measures within the defined impact areas. Hence, an adapted regional planning is strongly recommended. In parallel with this measure, the general public should be informed about the potential hazards and risks by means of awareness-raising.

A pilot project in Heerlen aims to obtain further insights and a calibration of the mining conditions of stopes assigned to impact category EK 1. A (satellite-based) early warning system might support the early detection of specific ground movements.

Prior to new construction projects in impact areas, an adapted site investigation has to be conducted. If necessary, the construction has to be adapted to meet certain static requirements. In the case of a Top Event, immediate measures like construction support work should be implemented.

In general, the stabilisation of underground mine voids can be accomplished by using techniques of foundation engineering such as grouting. However, the application of these measures requires a more or less detailed knowledge of the position and distribution of the underground mine voids. However, the costs for an area-wide exploration of the impact-relevant mine voids are out of proportion to the low absolute risk related to near-surface mine workings.

Instead of that, **administrative tools** should be implemented to prevent new risks created by the construction of new buildings or other changes in land use. Therefore, in the historical mining area, it is strongly recommended that any project (construction planning or other development planning) inside the “Potential im-

“Development Freeze” is forbidden, unless investigations and remediation measures are performed (“Development Freeze”).

Inside the “Potential impact areas EK 3” any project (construction planning or other development planning) should be forbidden (“Development Freeze”), unless an expert opinion is obtained and an inspection of the excavation pit is performed.

All recommendations and regulations mentioned above for the “Historical near-surface mining area” are restricted to the former concessions of “Domaniale” and “Neu Prick” and located in the municipal area of Kerkrade.

For taking into account the risks from “industrial” near-surface mining, there should be a full integration of the impact areas into regional development planning. The general public should be informed by awareness-raising measures. Certain development regulations should be formulated for building projects within the impact areas of “industrial” near-surface mining. In general, there should be a reaction to every damage event.

4.3.4 “Smaller mining relicts”

As an extra to the detailed investigation of the approx. 7.700 mining documents, four types of “Smaller mining relicts” were identified:

- **“Upward Drillings”**: Smaller drillings from mine voids upwards to the top of the Carboniferous bedrock;
- **“Downward Drillings”**: Larger drillings from the ground surface downwards to the top of the Carboniferous bedrock;
- **“Drempels and Scheuren”**: Discontinuities at the ground surface observed and registered during or shortly after active mining;

- **“Verzakkingen”**: Subsidences and sinkholes at the ground surface observed and registered during or shortly after active mining.

All these detected “Smaller mining relicts” were digitised and integrated into a GIS. The locations of all drillings are depicted in Plan 4; “Drempels” and “Verzakkingen” are shown in Plan 5.

“Upward drillings” are links between underground mine voids and the overburden, often carried out in a narrow drilling grid, and later sealed by simple techniques like wooden plugs. The total number of these upward drillings adds up to about 7.250; for all points, an accuracy of position of 5 m is assumed and designed in the GIS. Especially after a failure of the wooden plugs, these upward drillings are supposed to be preferential pathways for flowable material, and therefore might enhance suffosion.

“Downward drillings” can be seen as small-scale shafts, although usually not connected to underground mine voids. They constitute a link between the ground surface and the Carboniferous bedrock. The total number of these downward drillings amounts to 274; for all points, an accuracy of position of 20 m is assumed and designed in the GIS. For already-existing buildings there is no future impact to expect. But for new buildings, if the foundation, or particularly the piles, are unfortunately placed on or inside such a downward drilling, this might lead to significant problems.

For the handling of these mining relicts, the following recommendations are made:

- The knowledge about both kinds of drillings should be given to the competent and responsible authorities at the municipal, provincial, and state levels.
- If damage events emerge or if damage is reported, especially that related to subsidence, the local situation with regard to drillings should be checked.

- The authorities should arrange a visual inspection of each excavation pit by a geotechnical expert and/or mining expert if a “Downward Drilling” is documented in the affected property (this recommendation does not refer to “Upward drillings”).

“Drempels and Scheuren” are discontinuities, cracks or fissures observed at the ground surface while “Verzakkingen” are subsidences or sinkholes, both observed during or shortly after active mining. Both of these mining relicts do not constitute a hazard by themselves, but they are clear indicators of a weakened subsoil thus generally inducing “geotechnical zones of weakness”.

For the handling of these mining relicts some recommendations are given:

- Knowledge should be made available for the competent and responsible authorities at the municipal, provincial, and state levels.
- If damage events emerge or if damage is reported, related to both subsidence or ground heave, the local situation with regard to these mining relicts should be checked.
- Both types of mining relicts have to be considered by the planners of building projects.
- The authorities should arrange a visual inspection of each excavation pit by a geotechnical expert and/or mining expert if a “Verzakking” is documented in the affected property (this recommendation does not refer to “Drempels and Scheuren”).

4.4 Groundwater quality (WG 5.2.4)

4.4.1 Approach

The dewatering of the active mines in the Carboniferous bedrock has led to an increased inflow of groundwater from the overburden and hence a deepening of the groundwater level in the overburden. With the rise of the mine water, this effect will be reversed. Depending on the mine water levels that develop in the level of the mines, groundwater levels in the overburden will rise, and mine water might infiltrate to the groundwater bodies of the overburden. Due to man-made changes in the hydraulic system of the Carboniferous, these effects will be different from the natural situation.

The main potential impacts on groundwater that arise from this scenario are a wetting of the surface and a change of groundwater quality that might influence groundwater extractions. Potential wetting is discussed in Subsection 4.5.

Mine water can have a high salt content and can contain heavy metals or additives used in the mining industry. Mine water can be very acidic and deoxidised. If mine water flows through covering layers and shallow groundwater reservoirs, and is mixed with water from shallow groundwater reservoirs, several hydro-chemical reactions will take place, such as the dissolution and precipitation of minerals. These reactions might change groundwater quality, and have an influence on existing groundwater extractions.

For the risk assessment, it is important to know how far the water in the mines will rise, and what the consequences will be for the groundwater level in South Limburg. Furthermore, it is necessary to assess whether the rising mine water will infiltrate into the overburden, and to what extent this affects the quality of the groundwater in the overburden.

The occurrence of an upward flow of mine water is also determined by the level of the shallow groundwater. As long as the shallow groundwater level is higher than the mine water level in the Carboniferous layer, no mine water will infiltrate into the upper groundwater bodies. Conversely, when the level in the Carboniferous formation is higher than the shallow groundwater level, groundwater quality in the overburden may be affected.

With respect to the above described major effects expected due to rising mine water, a scenario analysis was carried out in order to obtain insight into the effects of the rising mine water levels. The conditions for the occurrence of the different scenarios were investigated by the three-dimensional subsurface model IBRAHYM. The model was used to review the following matters:

- under what conditions the described scenarios/after-effects can occur;
- identification of the “potential impact areas”;
- evaluation of the possible “consequences”.

Finally, the measures that can be taken to reduce or stop change in the quality of the groundwater and the increase in its level were investigated, and a proposal for appropriate monitoring is presented.

4.4.2 Hydrogeological system

In the level of the Carboniferous, all the mines of the South Limburg mining district are still connected to each other at different levels and form a uniform basin. The only exceptions are the Maurits mine and the northeastern part of the Hendrik mine, northeast of the Feldbiß, which have been disconnected during mine closure by dams. The man-made hydraulic connections are spread over a wide area. They are the main factors of the actual hydraulic system in the mining district and control the effects of rising mine water.

The hydrogeological system of the overburden is characterised by a complex layering of several groundwater-bearing (aquifer) and sealing layers from the Cretaceous to the Quaternary. In the Tertiary layers more, or less one groundwater body is developed (1st aquifer). The Cretaceous formations of Maastricht and Houthem are often referred to as the 2nd aquifer within the investigation area. Their distribution is of main importance for groundwater extraction southwest of the Heerlerheide fault. There are only a few available groundwater monitoring wells. Generally, the groundwater levels in the deep groundwater reservoirs are influenced by several factors including long-term fluctuations, deep groundwater extraction, and the effect of rising mine water. Until now, there has been no mine water flow from the basement to the overlying groundwater reservoirs in the overburden due to the higher hydraulic potential in the overburden.

- The current flow system

The current knowledge about the groundwater flow system - before groundwater modelling was performed - is presented in Fig. 20.

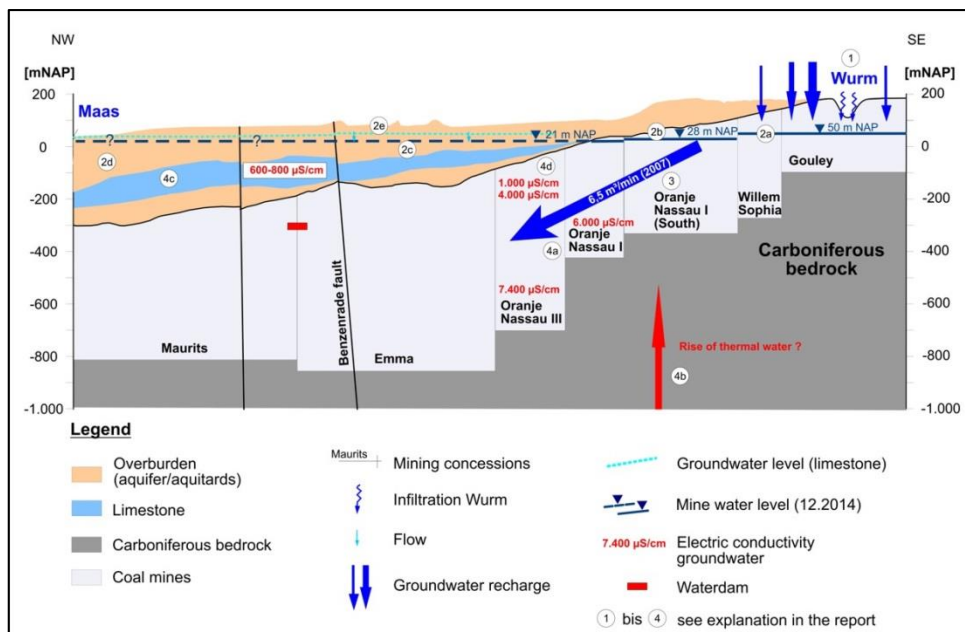


Fig. 20: Schematic representation of the current status of the ground-/mine water flow system

This is, however, a transient situation, as the mine water levels are still rising. The characteristics of the actual flow regime can be described as follows (Fig. 20):

- (1) The highest groundwater recharge occurs in the area where the overburden is missing (14 km²), and in the southeast where the overburden is thin. Water infiltrates from the Wurm, the floodplain of the Wurm and its smaller tributaries, but the magnitude of this infiltration cannot be quantified.
- (2a) The mine water level in the southeast in 12.2014 was 50 mNAP (Von-Goerschen-Schacht, Gouley-Laurweg).
- (2b) The groundwater gradient is oriented to the northwest. The mine water level in the Oranje Nassau I (South) mine in 12.2014 was 28 mNAP. The Carboniferous was not yet fully submerged.
- (2c) In this area the Carboniferous bedrock was completely flooded. The confined water level was about 21 mNAP in 12.2014.
- (2d) The mine water level near the Maurits mine (without a measured mine water level) is assumed to be at a similar level as in the Emma mine.
- (2e) The groundwater level in the main aquifer (Maastricht) drops from 130 mNAP to 30 mNAP near the Maas. The groundwater is highly confined. The flow direction in 2015 was still downward.
- (3) The current inflow to the basement and the mines is approx. 6,5 m³/min (evaluation of pump tests in the Von-Goerschen-Schacht). In the future the inflow will be lower as the gradient gets smaller (about 3 to 4 m³/min).
- (4a) According to the measurements, the electric conductivity in Oranje Nassau I and III increases with depth from 4.000 µS/cm up to 7.400 µS/cm.
- (4b) This indicates that the mineral inflow of deep thermal water is still active to a small degree. As the mine water level rises further, the inflow will become lower.

(4c) In the main aquifer (Maastricht) the electric conductivity is about 600 - 800 $\mu\text{S}/\text{cm}$.

(4d) The mine water near the top of the Carboniferous has an electric conductivity of about 1.000 $\mu\text{S}/\text{cm}$.

- The future steady-state situation

Based on the knowledge of the hydrogeological system, the hypothesis for the final steady-state situation is proposed. The final situation is defined as the situation in which the mine water has reached its highest level and the groundwater system is in equilibrium again (Fig. 21).

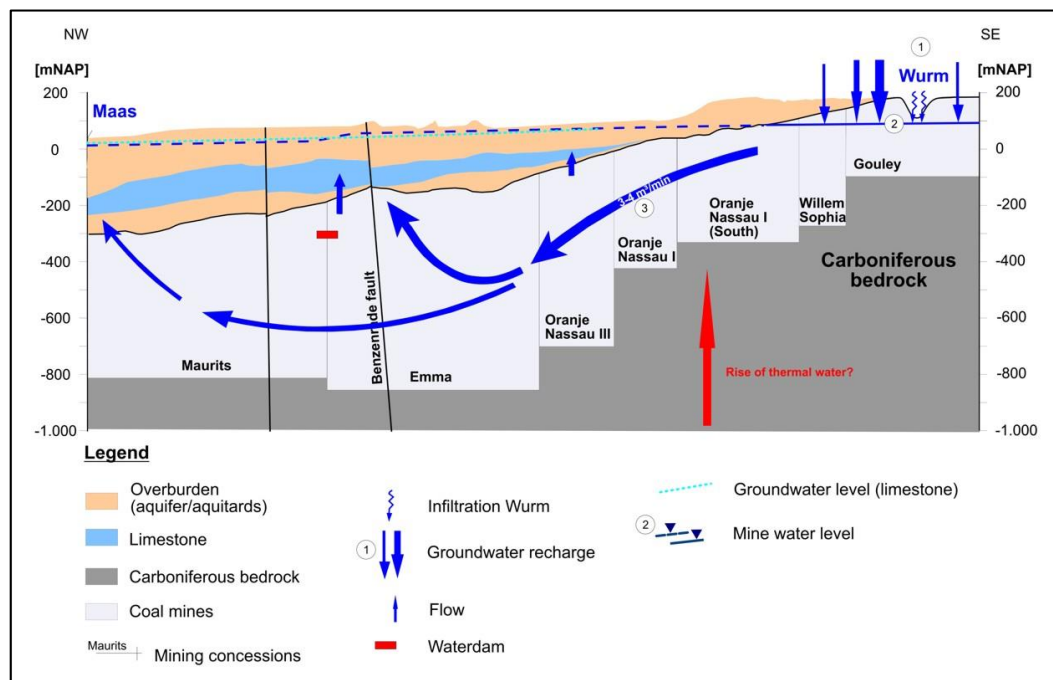


Fig. 21: Schematic representation of the hypothetical final situation of the confined ground-/mine water flow system (average case)

The main recharge is delivered from the southeast (Wurm river valley); the recharge rate is assumed to be 3 to 4 m^3/min (ROSNER, 2011). This situation supposes that the mine water level in the Carboniferous will end up higher than the near-surface groundwater level in the central part of the South Limburg mining

district but will not exceed the surface level. Due to the hydraulic barrier between the Emma and the Maurits mines, the upflow of mine water might concentrate in the Emma area.

4.4.3 Groundwater model

For the modelling of the influence of mine water rise on the groundwater situation in the overburden, the regional groundwater model IBRAHYM was used. IBRAHYM describes the groundwater system of the Province of Limburg. It has been developed by TNO/Deltares, Alterra, and Royal Haskoning. IBRAHYM contains the overburden, divided into 19 model layers, based on REGIS-II v2.1. The Aachen Formation forms the bottom of the original IBRAHYM model. In order to model mine water rise, two layers have been added to the model to include the Carboniferous:

- Basement above the mining zone (thickness 20 m, model layer 20);
- Mining zone (thickness 900 m, model layer 21).

Both these layers, the basement above the mining zone and the mining zone, have been given a conductivity of $1 \cdot 10^{-3}$ m/d. Areas with large inflow from the overburden documented in the mine maps (“hydraulic windows”) are taken into account in the model. These areas are assigned to model layer 20 with a conductivity of 5 m/d.

A sensitivity analysis was performed with the groundwater model to define several scenarios which cover the variety of the plausible approaches. The goal of the analysis was to determine which factors most strongly influence the mine water levels. It was determined that the hydraulic conductivity of the Carboniferous and the amount of future recharge to the Carboniferous formation were high-

ly influential. Three scenarios - worst case/best case/average case - have been defined for the final state when the mine water rise finishes, covering different approaches for the maximum rise of the mine water level, the amount of recharge, and the hydraulic conductivity of the Carboniferous.

All scenarios are steady-state calculations. The outcome of the calculations represents the future equilibrium situation of groundwater levels, after the rise of the mine water has ended. As a result the average case scenario is assumed to be the most realistic scenario. In this scenario, the mine water levels in the Carboniferous in the eastern concessions will rise to a maximum of about 80 mNAP. Between the Emma and Maurits concessions an unmined zone is located which operates as a hydraulic barrier (Fig. 22). Therefore, the hydraulic gradient between Emma and Maurits is very large. In the Maurits concession, the calculated mine water levels are about 40 to 50 mNAP.

The rise of the mine water results in an increase of the groundwater level in the near-surface groundwater reservoir. There is hardly any effect visible in the eastern mine concessions (Julia, Hendrik, Laura, Domaniale and Neu Prick). In these regions, an increase of between 0 and 0,10 m of the groundwater table is calculated with respect to the reference scenario (see Fig. 23, left). In the Maurits concession, increases of 0,25 to 0,5 m are calculated.

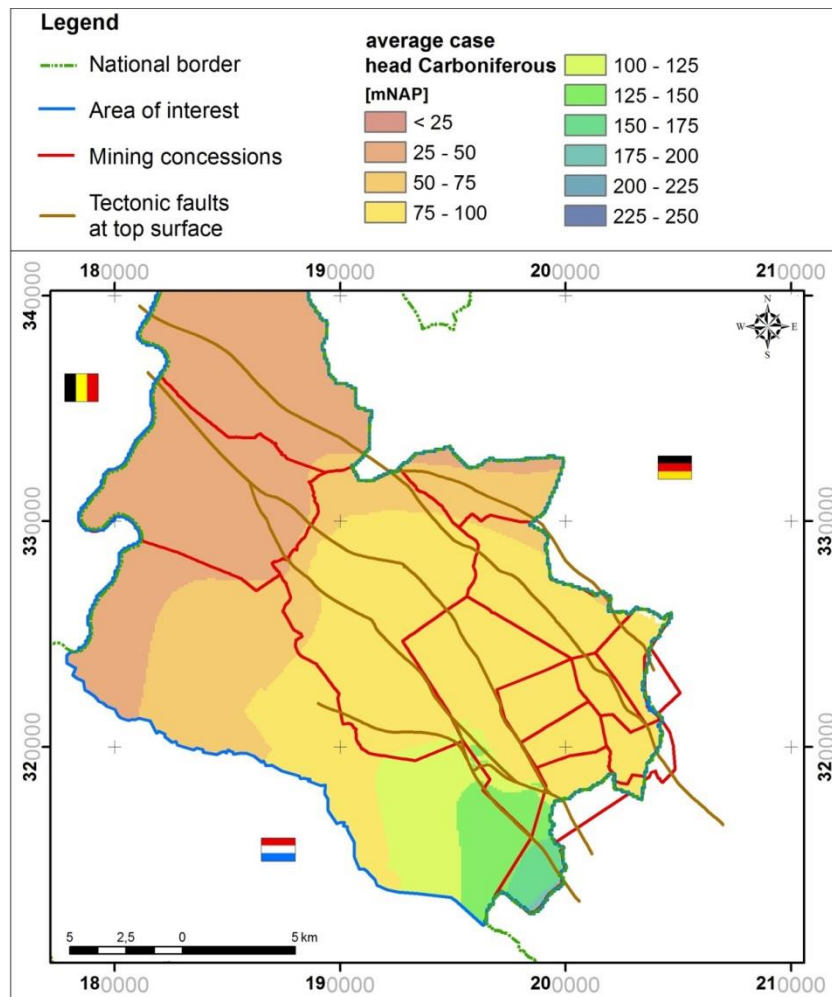


Fig. 22: Mine water pressure in the Carboniferous - average case scenario

The calculated rise of the (confined) water pressure in the limestone aquifer (aquifer 2) with respect to the reference scenario reaches maximum values of up to 3 to 9 m in the Maurits area (see Fig. 23, right). In the Emma concession, the maximum groundwater pressure increase is calculated to be 1 m.

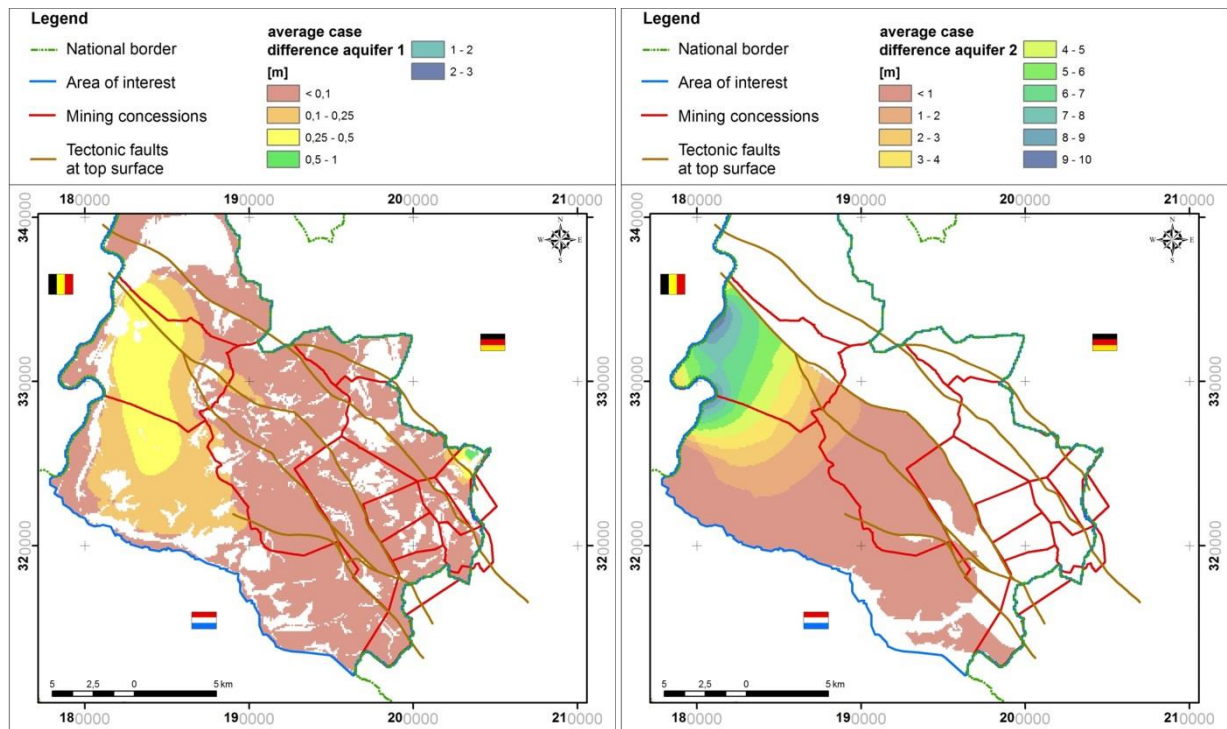


Fig. 23: Results for the average case scenario - increase in groundwater levels near to the surface (left) and increase of groundwater levels in the second (deep) limestone aquifer (right)

4.4.4 Assessment of impact potential

The composition of mine water is very different, compared with groundwater in shallow groundwater reservoirs nearby. Mine water can have a high salt content and can contain heavy metals or additives used in the mining industry. Mine water can be very acidic and deoxidised. If mine water flows through covering layers and shallow groundwater reservoirs, and is mixed with water from shallow groundwater reservoirs, several hydrochemical reactions might take place, such as dissolution and precipitation of minerals. These reactions will influence groundwater quality. The dissolution of minerals can cause contamination with heavy metals or arsenic.



The potential areas of influence for a change in groundwater quality are calculated with IBRAHYM. These areas of influence are calculated in the steady-state model, in this case, the final situation, in which mine water will not rise any further. Potential impact areas are defined as areas where a significant upward mine water flux is expected from the Carboniferous to the overburden. The upward flux is caused in the final situation if the level of the mine water is higher than the water levels in the shallow groundwater reservoir. This is observed mainly in the Emma concession. In other regions, the situation is the other way around: the groundwater level in the overlying groundwater reservoirs is higher than the piezometric heads in the Carboniferous, which results in a downward flux.

Based on the calculation with the groundwater model IBRAHYM and the differences in geohydrological conditions of the subsoil, two main potential impact areas are defined for the average case scenario (yellow area in Plan 6).

- potential impact area I:

The upward flux of mine water is calculated in an area southwest of the Heerlerheide fault. Groundwater from the limestone aquifer (the Maastricht Formation) in this area is being extracted by industry and the drinking water company WML. This area can be divided into an area south of the Benzenrade fault (area Ia) and an area between the Benzenrade fault and the Heerlerheide fault (area Ib).

- potential impact area II:

Here the upward flux of mine water is calculated in an area north of Heerlerheide fault.

The extent to which groundwater quality, within the potentially affected areas, can be influenced by rising mine water is dependent not just on the characteristics of the subsurface but also on geochemical processes. Based on the model calculations with IBRAHYM, streamlines were determined and the changes in

the chemical composition of mine water and in travel times were calculated. To determine the potential risks of mine water rising towards the groundwater reservoirs in the overburden, the following analyses were performed:

1. Possible effects on groundwater quality were identified. Based on the model schematisation the flow paths and travel time of mine water were determined.
2. The water balance of the groundwater model was analysed. Based on the fluxes as calculated by the groundwater model, the ratio between mine water and groundwater was calculated for the groundwater layers.
3. The ratio of mine water and groundwater was calculated, using the 3D transport model MT3DMS.
4. A hydrogeochemical simulation of mine water flowing upwards was performed with the PHREEQC program.
5. Finally chloride concentrations were calculated using the 3D transport model MT3DMS.

Calculations were made for an average situation (i.e. the most likely situation) and a worst-case situation. Based on 1D PHREEQC groundwater calculations, sulphate and chloride are identified to be the largest threat for the groundwater quality in the impact areas. Here an increase in the chloride and sulphate concentration was calculated, starting 30 years after the rise of mine water had ended, and gradually increasing during the next 70 to 100 years. In the most likely case, the concentrations of chloride can increase to a level of 700 mg/l at the Top Vaals/Bottom Maastricht. The concentrations of sulphate can increase to a maximum level of approx. 150 mg/l.

However, due to mixing it is to be expected that further upward flow and mixing with “limestone” water will decrease the concentration of sulphate and chloride. In the report, the consequences of a gradual increase of chloride and sulphate



concentrations for present groundwater extractions are investigated. The calculations show that, due to mixing, the concentrations of chloride and sulphate will not exceed 1 mg/l in impact area Ib. In area Ia there is no increase of chloride calculated. So, for groundwater extractions the consequences seem to be limited.

The mobility of most heavy metals depends on pH value (amongst others). A large change in the pH value is not to be expected: it will stay in the range 7 to 7,5, so the mobility of metals is limited. Besides low mobility, dilution plays an important role in the expected concentration in the Maastricht aquifer and extraction wells; it is not to be expected that measurable concentrations of trace elements from mine water will be detected in the abstracted water.

North of the Heerlerheide fault zone in impact area II, it is also likely to expect mine water will intrude in the overlying formations. In this area there are no (deeper) groundwater extractions at present, so there is no actual threat. Also in this area a further decrease of the concentrations will take place, due to mixing with shallow groundwater.

In the report it is emphasised that the outcome of the investigations is based on the results of calculations with different groundwater models. In groundwater model studies usually model results are calibrated and verified using measured groundwater level and water balances. This is done by recalculating an event or period that occurred at an earlier date.

In the case of the rising mine water, verification is barely possible. The mine water level is only measured in five shafts (shaft I Wilhelmina, shaft II Oranje Nassau I, shaft I Julia and Beerenbosch II and Willem II shafts (Domaniale)), meaning only in the eastern mine area. There are no data available, neither for the western part (concessions Emma and Maurits) nor for the Belgian concessions. In the overlying formations, measurements have been carried out on only a few

locations: namely, in the four groundwater monitoring wells of the “Mijnwater-meetnet” and in the area of the groundwater extractions from the Water company in the Voerendalerveld.

4.4.5 Bow-Tie-Analysis and monitoring plan

Considering the possible influence on the quality of the deep groundwater as a Top Event, the upward flow of mine water through layers with a higher conductivity especially in the Emma concession is the main Threat from rising mine water. As a result, extracted water by the drinking water company or industry may be influenced. The Bow-Tie-diagram can be seen from Appendix 1.

In practice, this Threat can only be mitigated by preventing further rise of mine water by initiating the pumping of mine water again; but this measure is regarded not to be adequate for the time being (see Section 5).

For mitigating or preventing the effects of mine water rise, the following recommendations are made:

- An important Threat is the presence of hydraulic windows, i.e. zones with higher permeability between the Carboniferous and the overlying groundwater reservoir in the overburden. Some of these hydraulic windows are identified in the report, but it cannot be excluded that more windows are present. It is advised to do geohydrological research when new groundwater extractions are being planned or the extraction of groundwater will increase.
- The authorities are advised to conduct a policy for the protection of groundwater extractions, which is an obligation of the Water Frame Work Directive and the Groundwater Directive, in “het Provinciaal Omgevingsplan Limburg” and the “gebiedsdossiers”.

- The Province of Limburg and the Water Board are advised to take in account the effects of rising mine water, when recalculating the protection zones of drinking water extractions.

A main part of prevention controls is the monitoring of deep groundwater and mine water, as only a sufficient knowledge about the hydraulic and hydrochemical situation underground can help to become aware of any changes over time.

- Monitoring

It is advised to set up an adequate groundwater monitoring system as a basis for the monitoring and handling of potential impacts from rising mine water on the groundwater of the overburden. As only few appropriate deep piezometers are available, it is recommend to install new piezometers that are screened in the Carboniferous formation, as well as in the basic layers of the overburden. It is advised to set up a groundwater monitoring system for the following reasons:

- These measurements give an insight into the actual situation and the groundwater levels in the future;
- Such a system can obtain information about the structure of the underground and parameters in an area where this information is currently missing, for example about the conductivity of the hydraulic windows. Based on this information, the groundwater model can evolve from the “conceptual model” to become a predicting model;
- Collect data about the groundwater quality and the development of the quality, especially in an area where possibly in the future the drinking water supply is affected, like the Voerendalerveld or around industrial groundwater extractions where groundwater is extracted for the production of food products. The measurement can form a basis for an early warning system;

- Deliver accurate information as a basis for other effects like induced seismicity and ground movements.

4.5 Groundwater quantity (WG 5.2.5)

4.5.1 Approach

Rising mine water can lead to a rise in groundwater levels in the overburden (formation above the Carboniferous Formation where coal seams are present). In regions with relatively high groundwater tables (near the surface), such as the valleys in South Limburg, a rise of the shallow groundwater level could lead to water nuisance. If and to what extent this effect occurs is highly dependent on the magnitude of the interaction between rising mine water levels and the groundwater levels in the deep groundwater reservoirs, as well as the interaction between the deep groundwater reservoirs and shallow groundwater. The secondary effects of rising groundwater levels on nature, urban areas, infrastructure and agriculture could occur.

The possible effects of mine water rise to shallow groundwater levels has been investigated with the 3-dimensional groundwater model of the subsurface of South Limburg, the IBRAHYM-model. Based upon the calculated groundwater level, a risk map was prepared of areas where groundwater levels are already shallow and will rise due to mine water rise. These areas are identified as potential impact areas for wetting.

4.5.2 Risk factors

The hydraulic and hydrogeological basics for the assessment of the potential impacts on the groundwater in the overburden due to rising mine water are described in Subsection 4.4. The most vulnerable areas with high groundwater levels of less than 3,5 m below surface level are shown in Fig. 24.

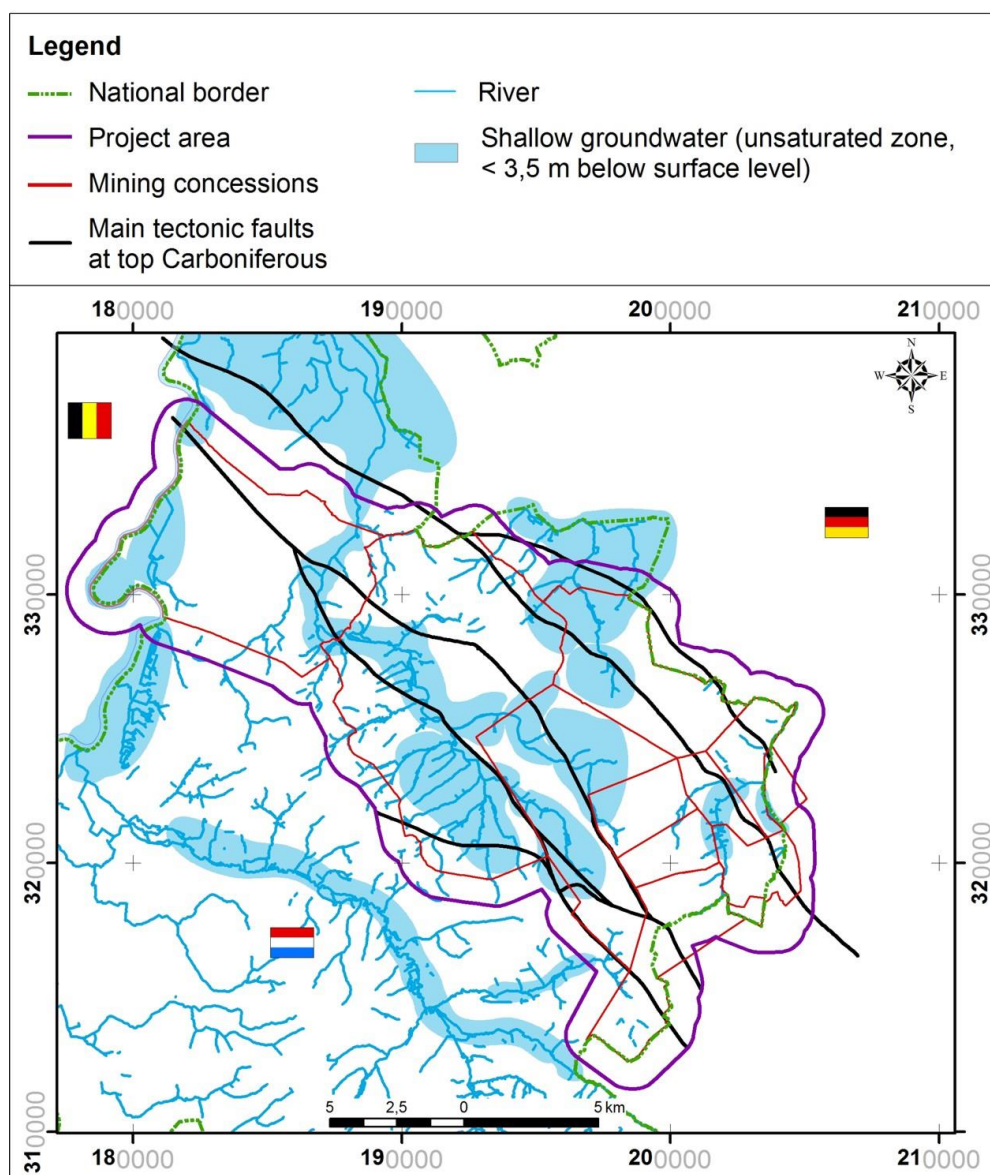


Fig. 24: Areas with thickness of the unsaturated zone < 3,5 m

In these areas an increase of groundwater level could (theoretically) cause the wetting of cellars, change of agriculture production (both positive or negative), or damage to nature.

Areas of interest with high groundwater tables are mostly located in the river valleys, both the smaller valleys like the Geleenbeek valley and the larger valleys like the Maas river valley (on the western border of the project area).

Main townships and villages are situated mostly on top of the plateaus. In several areas, buildings are also situated in river valleys or areas with a higher groundwater table: for example, in the towns of Hoensbroek, Schinveld, Nieuwstadt, and parts of the city of Sittard. In such areas, wet cellars might be a problem arising from rising groundwater levels.

Furthermore, areas with both a high groundwater table and an area of high natural value are of interest. Often nature reserves are situated in the river valleys. Change of the groundwater situation might affect the existing vegetation.

4.5.3 Assessment of impact potential

Based upon the calculated groundwater level and changes in groundwater levels, the potential impact area for wetting is defined as an area with relatively shallow groundwater levels (3,5 m below the surface or less) with a calculated rise of shallow groundwater level of about 0,1 m or more.

Calculations with the IBRAHYM model show that, in the most likely case (the average case), wetting can occur in the Geleenbeek Valley near Geleen and Schinnen, and locally near the river Maas (Plan 6). The rise of shallow groundwater levels will be relatively low: a maximum of between 0,1 and 0,25 m is calculated (see Fig. 23).

The largest calculated increase in the near-surface groundwater level level of 0,5 m occurs in the Maurits and Julia concessions (see Fig. 23) in areas where the groundwater table lies well below 3,5 m beneath the surface. This increase will therefore not lead to water nuisance.

In general, it is not to be expected that this will lead to severe damage to housing, nature, or agriculture.

4.5.4 Bow-Tie-Analysis and monitoring plan

For the Top Event wetting stream valleys, a Bow-Tie-Analysis has been carried out (Appendix 1). For the handling of potential water nuisance in view of prevention controls, recovery controls as well as escalation controls, the following recommendations are made:

- The knowledge about rising mine water and potential impact areas should be made available for the municipalities, province, and Water Board;
- If wetting occurs or is predicted, the local situation with regard to geohydrology should be checked and the relationship between mine water rise - increase of groundwater - and damage should be investigated;
- Impact areas need to be considered by the planners of building projects, especially in areas where local water nuisance already occurs;
- If wet cellars occur, drainage measures can be taken to prevent further damage.

It is advised to develop a regional monitoring system to measure the level of the mine water, so as to better predict future changes of shallow groundwater levels. Since water nuisance largely depends on local conditions like elevation, ground-

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water level, local drainage, heavy rainfall, etc., it is not possible to specify general measures which can be taken to prevent rising groundwater or mitigate the consequences; therefore, it is not necessary to set up local groundwater monitoring networks.

4.6 Mine gas (WG 5.2.6)

4.6.1 Approach

Coal seams tend to have various gas contents that are partly released by mining operations. Volatile mine gas finds its way to the shafts, and may charge the mine air with a methane-air mixture. After mine closure, residual gas will remain in the mine workings. Consequently, further gas is released over a period of up to several decades, and in the unventilated abandoned mine workings the gas may be enriched. If methane is oxidised, carbon dioxide (CO₂) is generated and, as a secondary effect, a harmful reduced concentration of oxygen in the air might emerge.

At low air pressure, barometric changes cause the release of gas mixtures from abandoned mines to the surface or, at high air pressure, air influx into abandoned mine workings. This airflow is enabled only if flow paths connect the former workings to the ground surface. In general, a diffuse gas emission in open areas is not harmful to humans and to the environment. A potential hazard only occurs when gas is allowed to accumulate, e.g. in underground structures.

Based on the evaluation of the actual composition of mine gas that is released from unflooded mine workings, as well as on a spatial assessment of still unflooded mine workings, different hazardous degassing areas are specified. Abandoned mine shafts have a special significance in this assessment since they generally provide a preferential path for the migration of mine gas. Further preferential paths for the migration of mine gas might be associated with the occurrence of a new sinkhole, with “Drempels” or with “Downward drillings” (see Subsection 4.3.4).

A Bow-Tie-diagram has been developed that revolves around the Top Event “Gas trapping in building”; furthermore, some (technical) Control measures are presented.

4.6.2 Data basis and conducted measurements

Due to the lack of measurement procedures for mine gas prior to the 1970s, there are hardly any data on the gas content of the coal seams in South Limburg mining district. Hence, data were derived from the adjacent Aachen mining district, where pits were operating until the early 1990s. The data from the Aachen mining district revealed considerable gas content in those coal seams that are situated below a depth of 100 to 150 m under the Carboniferous bedrock surface. In contrast to the methane that is released from coal seams, microbial methane generation is considered to be insignificant in the South Limburg mining district.

The release of mine gas only takes place in mine voids that are not yet flooded by rising mine water. Owing to the advanced stage of mine water rise, larger parts of the South Limburg mining district have already been flooded up to the bedrock surface; hence, the release of mine gas has ceased there.

However, in the southeastern part of the mining district, mine water currently has not yet reached the surface of the Carboniferous bedrock, i.e. only the deeper mine workings are flooded, while some mine workings close to the surface of the Carboniferous bedrock remain unflooded. An overlay analysis of the mine water level in 12.2014 and the level of existing mine workings revealed the area in which degassing might take place up to the present day. In addition, the flooding condition of mine workings was constructed for the final state of mine water rise (“average case”, 80 mNAP).

Based on the assessment of the backfill column of the shafts, as well as on the respective mine water level, 13 industrial shafts and all historical mine shafts were identified to be potential paths for mine gas.

To assess the actual gas content in the still unflooded mine workings, two measurement campaigns were conducted on 29.04.2015 and 07.07.2015, respectively. The measurements were conducted using the water gauge pipes that are installed in the Beerenbosch II and Willem II shafts (Domaniale), shaft II of the Julia coal mine and shaft I of Oranje Nassau I; the measured gas concentrations are given by Tab. 2.

Tab. 2: Gas concentrations in the mine gauge pipes

Shaft	Inspection-date	CH ₄ [vol.-%]	CO ₂ [vol.-%]	O ₂ [vol.-%]	Water level [mNAP]
Julia II (Laura-Julia)	29.04.2015	-----	0,12	20,8	13,5 (overburden)
Shaft II (Oranje Nassau I)	29.04.2015	-----	0,04	20,9	22,0 (overburden)
Shaft I (Wilhelmina)	29.04.2015	-----	0,22	17,7	29,9 (overburden)
Beerenbosch II (Domaniale)	07.07.2015	-----	0,06	19,9	39,3 (Carboniferous)
Willem II	29.04.2015	0,03	10,3	1,0	39,3
(Domaniale)	07.07.2015	0,08	10,6	1,3	(Carboniferous)

Assessing three recent gas leakage incidents, only one incident (in shaft II of Oranje Nassau I in 1979) was clearly attributable to the degassing of the unflooded mine workings.

4.6.3 Assessment of the present-day degassing situation

Since the release of mine gas heavily depends on the mine water level, the South Limburg mining district can be divided into three areas according to the overlay-analysis; the areas are depicted in Fig 25.

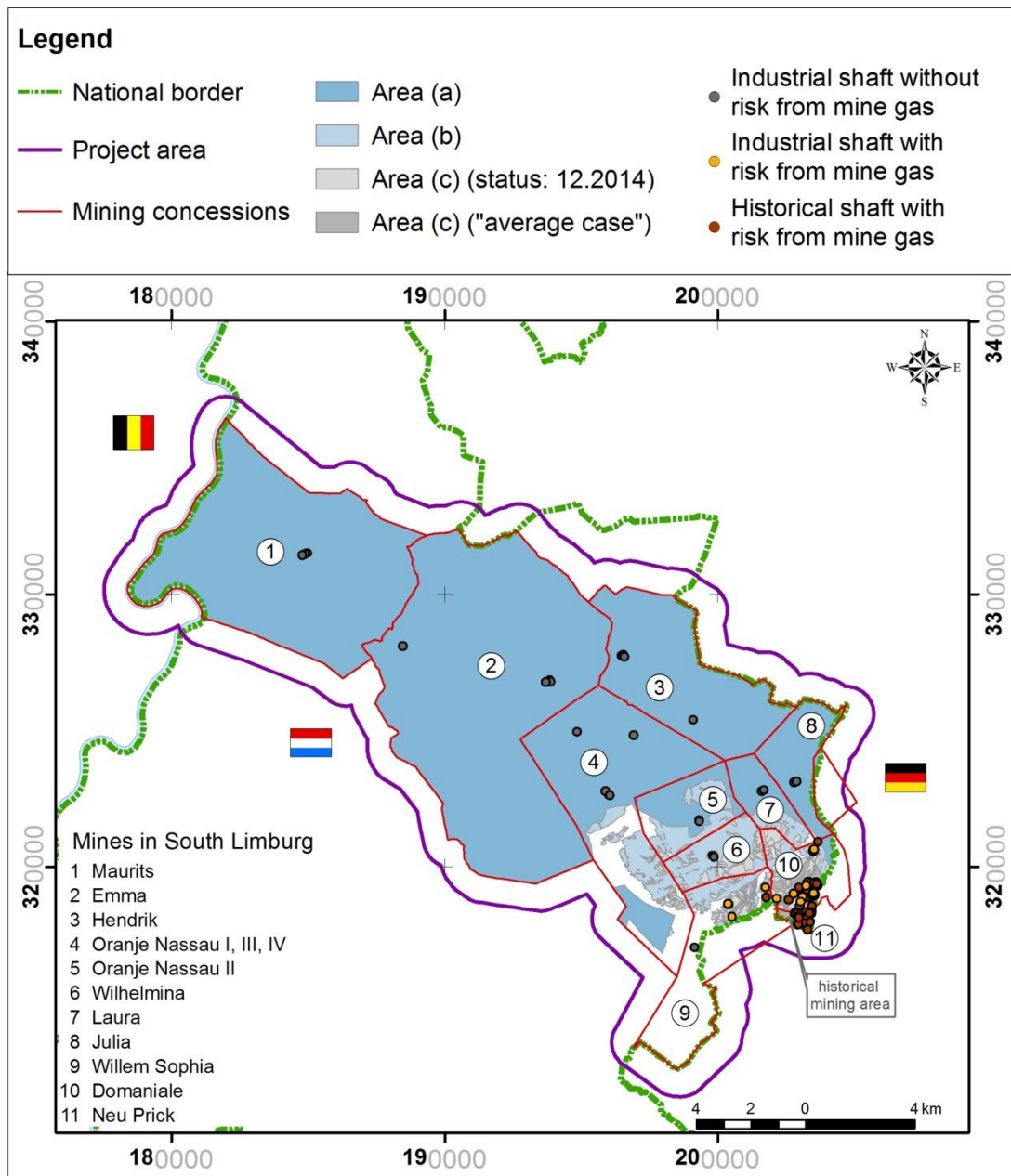


Fig. 25: Areas (a), (b) and (c) and evaluation of shafts concerning their degassing

The following areas can be distinguished:

- (a) areas with rise of the mine water level into the overburden strata;
- (b) areas with flooding of all mine workings, although the mine water level is still below the overburden;
- (c) areas with unflooded mine workings.

In category (a) no methane release will take place.

In the areas categorised (b), un-flooded coal seams may be found which can still release methane. Due to the flooding of the underground workings, however, no more voids for possible gas storage will exist.

Category (c) concerns the areas with open, unflooded underground structures. In these areas certain gas mixtures exist. Their pressure corresponds with barometric conditions. The gas mixture generally consists of nitrogen as a consequence of the low oxygen concentration. Methane is represented only in low and non-hazardous concentration. Nevertheless, low oxygen/high carbondioxide gas mixtures indicate the risk of suffocation. An overview of the areas categorised (c) is also given by Plan 7.

The areas of category (b) and category (c) are generally limited to the southeastern part of the South Limburg mining district. In this delimited area the risk of degassing exists, and the risk decreases with the further rise of the mine water level and therefore decreases over time. Nevertheless, degassing is considered to be possible in the whole historical mining area in Kerkrade for an unlimited period of time.

Concerning mine shafts with the potential for degassing, rising mine water causes no change, i.e. those shafts that were identified to be potential paths for the



migration of mine gas will also be potential migration paths in the future. In accordance with the procedure in North Rhine-Westphalia, “Gas-emission-protection-zone” is assigned to the respective shafts.

4.6.4 Bow-Tie-Analysis on the hazard of mine gas and further recommendations

The risk assessment is based on an analysis of the areas in which potential hazards from mine gas still might emerge.

In terms of the Bow-Tie-Analysis, the accumulation of gas in (underground) structures is defined to be the Top Event; in the Bow-Tie-diagram this Top Event is summarised as “Gas trapping in building”; the Bow-Tie-diagram is depicted in Appendix 1.

The potential Threats are related to different flow paths of mine gas. One can differentiate between:

- A flow path that enables mine gas to enter an (underground) structure; and
- A flow path that enables a spatially concentrated degassing of mine gas.

Once mine gas has accumulated in an (underground) structure, there are, in general, two potential Consequences. These Consequences depend on the gas mixture. One can differentiate between explosions and damage to persons/injuries. Social unrest is regarded as additional Consequence.

However, there are several Controls for the Top Event related to gas in the subsurface. Prior to construction projects in potential impact areas, the builder has to be aware of the potential Hazard “gas in the subsurface”. Building regulations, as well as an appropriate regional development planning, are considered to be useful



Prevention Controls, i.e. the respective authorities have to notify whether there is a potential danger of degassing in a to-be-developed building area or not. As the case may be, it will be necessary to comply with certain building regulations.

A further important Prevention Control is raising the awareness of drilling companies. Any drilling company has to be aware of the dangers that are related to drilling work in the potential impact areas. The gas content should be measured during construction.

As rising mine water diminishes the area that is potentially affected by degassing, hence, monitoring the mine water level is a useful way to keep track of the area that is currently affected by degassing.

A basic Recovery Control is the measurement of the gas composition in enclosed spaces. In general, all persons who live inside the potential impact areas should be informed about the potential dangers of mine gas, and should be able to act properly when encountering a hazardous area (e.g. avoidance of ignition sources).

The report gives further (monitoring) recommendations that are clearly divided into those concerning existing buildings and those concerning new construction projects.

For **existing buildings inside „Gas-emission-protection-zones“** an inventory of relevant cracks or fissures in the walls or the bottom slabs of the buildings is recommended. Partly damaged buildings are the main target point for monitoring measures, i.e. semi-annual gas measurements detecting the constituents methane, oxygen, and carbon dioxide.



Existing sewage systems inside the delimited area should be checked by using a portable measuring device and be integrated into a monitoring-system if alarming concentrations are noticed.

For new construction projects **administrative tools** should be implemented to prevent new risks caused by the construction of new buildings, new sewage systems, or other changes in land use. Therefore, it is recommended that any project (construction planning or other development planning) inside the „Gas-emission-protection-zones“ of the relevant shafts is forbidden unless safeguarding measures are implemented (“Development Freeze”). Furthermore, monitoring has to be carried out during the whole construction phase. For constructions that are equipped with safeguarding measures, no more monitoring is required.

If **drill holes and foundation piles** in the delimited area are sunken through the uppermost aquiclude, measurements of the CO₂- and O₂-concentration, as well as of the concentration of flammable gases, have to be performed during the construction work using an appropriate portable device. The same is recommended if a new sinkhole might develop inside the delimited area.

“**Drempels**” or “**Downward drillings**” may also be preferential pathways for gas, but due to their existing large number neither monitoring nor other measures are recommended as long as there is no definite evidence for gas emissions.

4.7 Small earthquakes (WG 5.2.7)

4.7.1 Approach

The working group on small earthquakes has made a temporal and spatial analysis of groundwater level development, seismic data, ground uplift, and fault data to determine a possible relationship between the occurrence of earthquakes and the rising mine water level.

The main subject was the discussion of possible interactions between rising mine water and two earthquake swarms around Voerendaal. The hypothesis derived from these events was: rising mine water triggers small earthquakes in a seismically active area. To prove or reject this hypothesis, the study looked at two possible mechanisms that could have triggered the earthquake swarms:

- (1) exceedance of the critical state of the active faults due to increasing pore (water) pressure and
- (2) increase and shift in mass due to groundwater level rise as a driving (energy) source.

A decrease in shear strength does not necessarily result in fault movement, because there should be a driving force. The main driving force for fault movement is the existing tectonic stress regime, which is extensional (horizontal), causing normal fault movement. In addition to the tectonic stress the mass shift (vertical) could be an additional driving force.

4.7.2 Analysis of the seismic setting

The analysis followed multiple approaches to discuss the hypothesis, as there are no acknowledged methods or quantifiable experiences from other mining regions for the investigation of seismic events due to rising mine water.

- Spatial and temporal analysis

In general, the South Limburg mining district is affected by natural seismicity. It is situated at the southern part of the Roer Valley Graben structure. There are some important active faults in the area. Two earthquake swarms have occurred in the past, one smaller swarm around 1985-1986 and a larger swarm around 2000-2002, known as the Voerendaal swarms (Fig. 26).

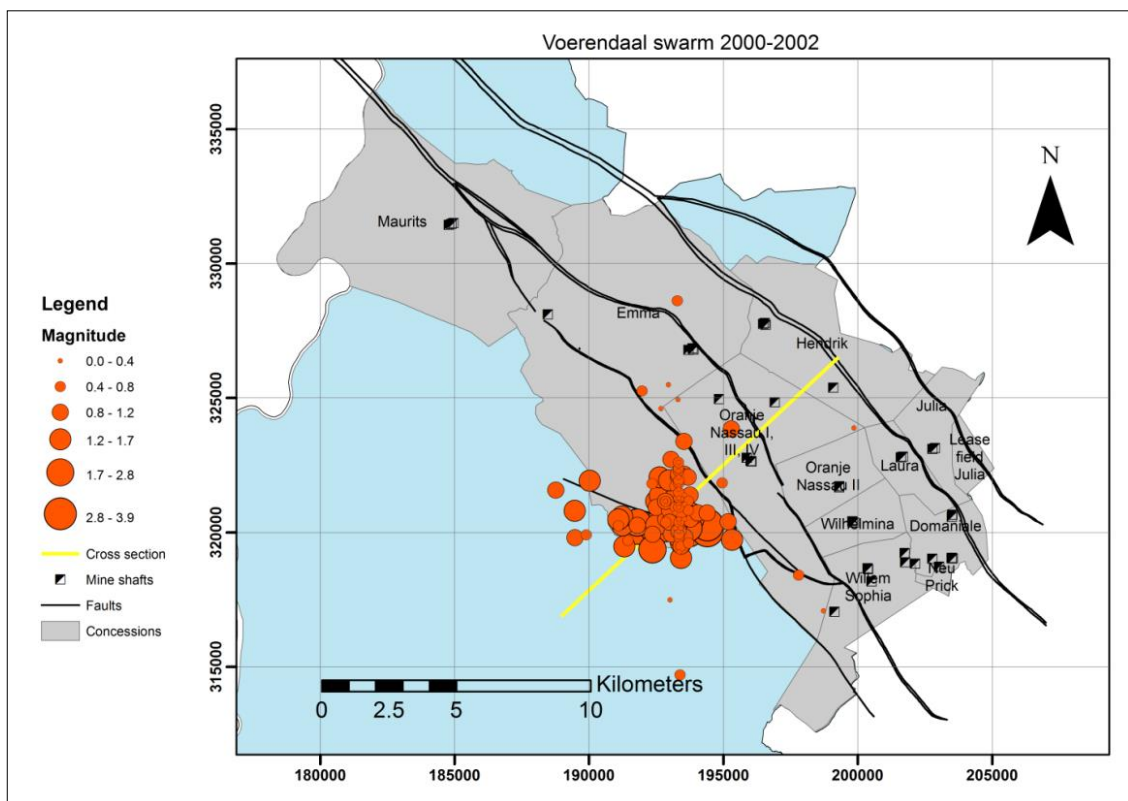


Fig. 26: Location of the 2000 - 2001 epicentres of the Voerendaal swarm with respect to the faults and mining areas

These swarms appear to be correlated to the Kunrader fault. The largest earthquake of the second swarm (M_L 3,9, 23.06.2001) has resulted in damage to houses and buildings, but there were no casualties.

The seismicity registered by the KNMI was compared to the variation in groundwater level over time, as well as to the ground deformations. Spatially, the seismicity was plotted in maps with the ground deformations. Temporally, the first Voerendaal swarm (1985 - 1986) appeared about 11 to 12 years after the main mine water increase of 1974 - 1975; and the second Voerendaal swarm (2000 - 2002) about 5 to 6 years after the main mine water rise of 1995 (Fig. 27).

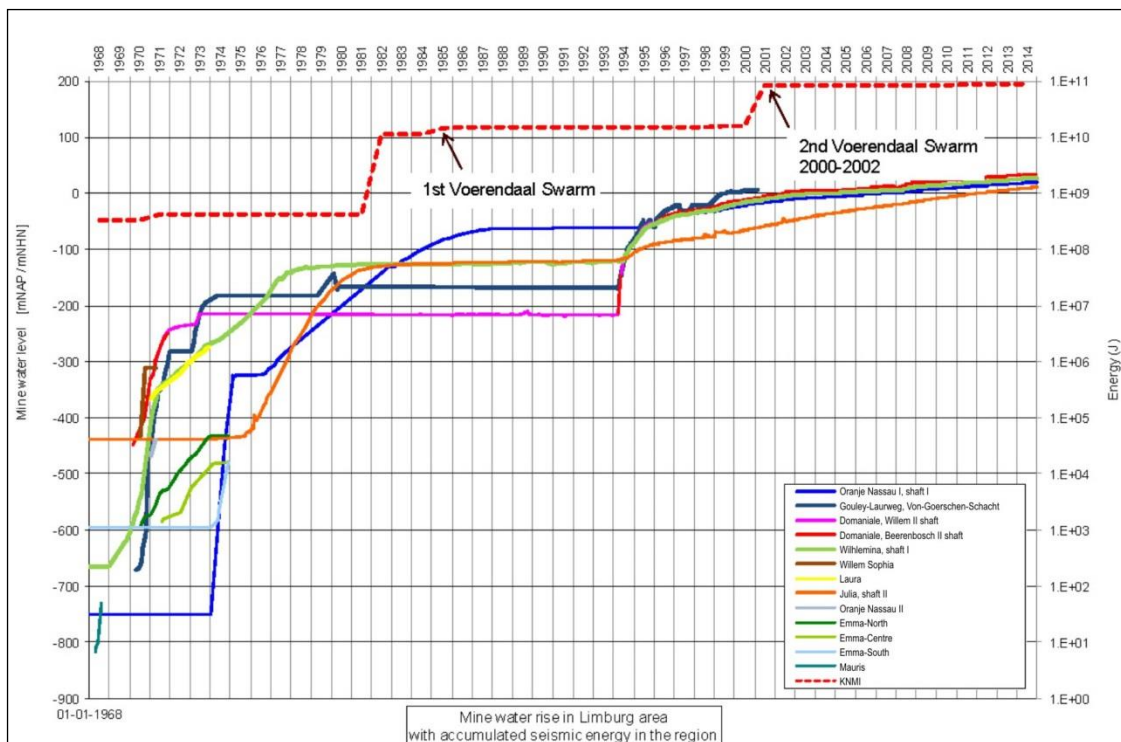


Fig. 27: Mine water rise with accumulated yearly seismic energy (red dashed line) from the KNMI catalogue

As a result of the temporal and spatial analysis, it was concluded that there is no clear correlation between ground heave, subsidence, mine water rise and seismicity.

- Stress analysis

The stress analysis shows that the Kunrader fault near Voerendaal has an apparent dip with respect to the general stress field, which makes it more prone to slip than the other faults in the area. Furthermore, the analysis indicates that the Kunrader fault is close to its critical state. This means that an increase in the groundwater level as experienced in the past could cause the fault to exceed its critical state and result in movement.

On the other hand, mining itself could have produced a critical stress regime along the fault. Mine water rise or even normal tectonic movement could have been the trigger for the observed swarms at the Kunrader fault.

However, the stress analysis does not provide an explanation for the time at which (swarms of) earthquakes occur. The stress analysis is based on many assumptions (for instance, the friction angle of the fault), since not much is known about the exact characteristics of the Kunrader fault or other active faults in the area. Therefore, this analysis cannot show a significant correlation between rising mine water and seismicity in the Limburg mining district.

- Mass shift approach

The mass shift caused by the increase in groundwater level on the north side of the Kunrader fault has been compared with other data from induced seismicity. Data from the two Voerendaal swarms appear to be related to data from induced events from normal stress fields and, tentatively, the Voerendaal events could thus also be classified as “induced events”.

The energy balance analysis does not provide an explanation for the location at which (swarms of) earthquakes occur. However, it does suggest that earthquakes occur with some delay after an increase in the rate at which energy is supplied to

the system by water level rise. Nevertheless, the total amount of potential energy put into the system due to the increase in mine water level is many times larger than the amount of energy released by seismicity.

- Conclusions

The two mechanisms investigated in this study (fault movement due to a decrease in shear resistance in faults and increase in mass due to a rise in the level of the mine water) can theoretically explain the occurrence of the two earthquake swarms around Voerendaal. The sudden energy change in the two phases of quickly rising mine water in the 1970s and the 1990s is regarded as a potential trigger. Nevertheless, there are no clear indications of a significant correlation between rising mine water and the appearance of the Voerendaal swarms.

It is being discussed in theory that another swarm of the same size as 2000 - 2002 might occur in the future, based on the increase in mine water level. However, the amount of seismic energy that could be released and the expected magnitudes are not expected to increase the existing (natural) seismic hazard that is present in the area.

Therefore, it was concluded that induced seismicity due to mine water rise is not likely to occur in the future, and even if it does occur, it will not affect the existing seismic hazard in the area.

4.7.3 Bow-Tie-Analysis

With the results of the present investigations regarding the potential influence of rising mine water on “small earthquakes”, triggered earthquake has been defined as Top Event (see Appendix 1).

The consequence of a triggered earthquake might be damage to buildings, similar to what was experienced in Voerendaal during the $M_L=3,9$ earthquake of 23.06.2001.

It is not possible to prevent natural earthquakes. In the South Limburg area one has to accept this natural hazard. Induced seismicity is possible in theory, but if the increase in the mine water level is maintained at a gradual rate, the likelihood of such an occurrence is considered small. Therefore, a limitation of the future mine water rise, for instance by pumping, is not an adequate prevention control (see Section 5).

However, it remains important to carefully monitor the development of the mine water level, as well as the level of the groundwater in the overburden, especially near the Kunrader fault, as a major prevention control. This may help to better understand and assess future seismic events.

From a scientific and seismological point of view, it is, however, recommended to obtain a better understanding of the Kunrader fault. This can be done through the execution of a geophysical (seismic) survey across the Kunrader fault near Voerendaal. With an improved understanding of the fault system, a better analysis can be carried out with regard to the possible mechanisms leading to (induced) seismicity along this fault.

Possible recovery controls go together with the management of the already existing seismic risk in South Limburg. The natural existing seismic hazard in the area has to be factored into the construction of buildings and infrastructure.



The challenge here is that, to date, there are no guidelines for seismic-resistant design in force in the Netherlands. In the past, seismicity in the Netherlands was not considered high enough to require being taken into account in building norms or codes. Currently, a Dutch National Annex to Eurocode 8¹ is being formulated, but the status of this Annex is not clear. An initial step towards this national Annex has been made for the induced seismicity of the Groningen area in the form of the NPR. However, it is recommended that such an Annex should cover the whole of the Netherlands, especially the area with natural seismicity, i.e. the South Limburg area.

¹ Eurocode 8 is the European norm for the earthquake-resistant design of buildings, bridges and other infrastructure (NEN-EN 1998-1:2005 EN).

5 Future development of mine water rise

5.1 Prognosis of future mine water rise

A prognosis of the future development of the mine water level is delivered by WG 5.2.4/5.2.5 on the basis of the groundwater model IBRAHYM (see Subsection 4.4). According to the results of the most probable scenario (average case scenario), calculated with the groundwater model, the mine water level in the Carboniferous will rise to a maximum of about 80 mNAP in the southeastern concessions. Due to the high hydraulic conductivity in the mined Carboniferous bedrock, the mine water level is expected to be at a more or less uniform level of between 75 and 80 mNAP in the central and southeastern concessions. Between the Emma and the Maurits concessions an unmined zone exists which operates as a hydraulic barrier. Therefore, the hydraulic gradient between the Emma and the Maurits mines is very large. In the Maurits concession, the calculated mine water levels are about 40 and 50 mNAP. The results of the average case scenario calculations are shown in Fig. 28.

Compared with the present mine water level (about 40 mNAP in 12.2015), a further rise of 40 m is expected in the Domaniale concession. This means that the level of the river Wurm (110 mNAP) will not be reached within the future rise of the mine water. All mine water will flow towards the northwest; no mine water will leak into the Wurm river valley.

The scenarios calculated with the IBRAHYM model are steady-state calculations. The results of the calculations represent the future mine water level in the final equilibrium situation. Non-steady calculations which also provide the development of the mine water level over time have not been executed due to the disproportionate amount of time and effort involved in such calculations.

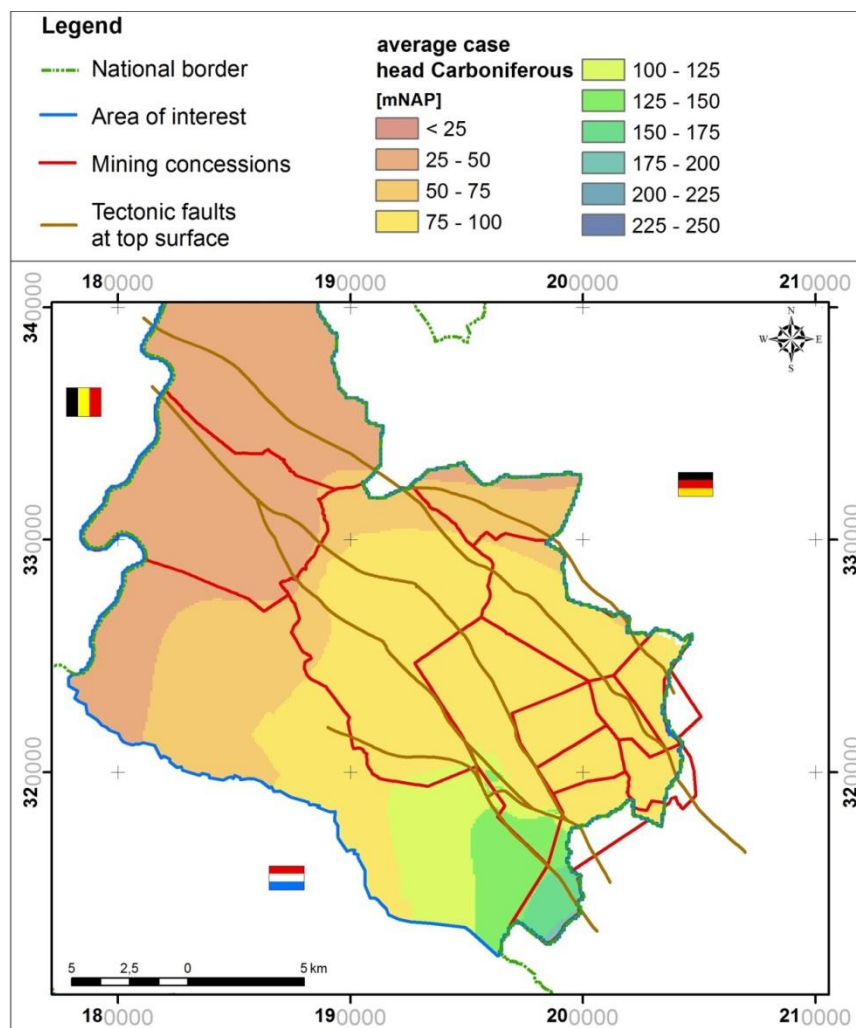


Fig. 28: Final state of mine water pressure in the Carboniferous according to the groundwater model (average case scenario)

A rough estimation of the time required to reach the final equilibrium state can only be done by an extrapolation of the development of mine water levels up till now, as is shown for Domaniale mine in Fig. 29.

Taking the average velocity of the mine water rise since 2008 of about 2,8 m/a, it will take about 14 more years until the final-state mine water level at 80 mNAP will be reached. This value can be regarded as a minimum time span. Actually, it

has to be expected that the velocity of the mine water rise will continue to decrease.

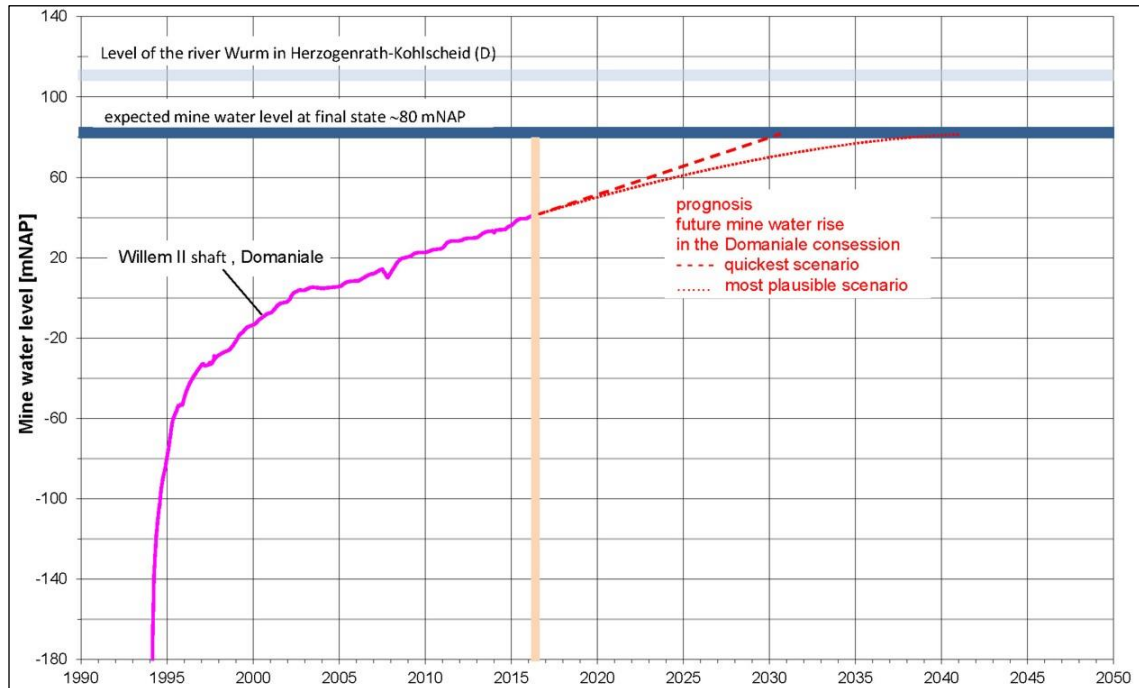


Fig. 29: Prognosis of future mine water rise (empirical estimation)

Therefore, a time span of at least 20 years can be expected until the final state of the mine water level will be reached.

5.2 Discussion of protective dewatering measures

5.2.1 Re-start pumping

The only measure to prevent any future impacts of rising mine water will be to stop mine water from rising further. This can only be achieved by re-start pumping, and discharging the mine water to the surface waters. Such a measure would be a perpetual obligation.



For the German territory (Aachen mining district), perpetual pumping was refused as a preventive measure due to the heavy impact on the surface water by the discharge of highly mineralised mine water and the perpetual impact on water economics by water abstraction from the natural underground sources.

Considering the possible impacts described in Section 4 the following benefits could be drawn from future pumping:

- Ground movements (WG 5.2.1)

Stopping the further rising of mine water would result in a stopping of ground heave; under these circumstances, no further impacts by differential ground heave would have to be expected.

- Mine shafts (WG 5.2.2)

Sinkholes can develop above and in the vicinity of old mine shafts independent of the mine water level. During the rise of mine water, critical mechanical situations might develop for a short time. But, in the long term, the flooding of a shaft fill could also mean a stress release due to the hydrostatic uplift forces, thus enhancing the stability situation of the shaft filling.

Furthermore, most of the old shafts in the Domaniale and Neu Prick concessions are supposed to be no deeper than 80 mNAP.

For all these reasons, protective pumping at a deeper depth than 80 mNAP is of restricted use only, in view of potential impacts from old mine shafts.

Regarding the industrial mine shafts, rising mine water might have a destabilising effect when the water level exceeds the respective sealing element and affects the non-cohesive backfill column. In this case, minor subsidence of the backfill column cannot be excluded. Hence, pumping measures would preserve the status quo.

- Near-surface mine workings (WG 5.2.3)

Potential impacts by near-surface mine workings are mainly restricted to the historical mining area in the Domaniale and Neu Prick concessions (project area 1; see Subsection 4.3). In this area the relevant mine workings are located in a level above 80 mNAP. Therefore, pumping would not have any effect on the impact potential of these near-surface mine workings.

Further potential impact areas are assigned for project areas 2 and 3 (see Subsection 4.3). Here, mine water is regarded to give rise to new, former back-filled voids. The loss of abutment, in turn, might weaken the overlying strata, and thus, may cause failure of the rock roof.

Furthermore, rising mine water is considered to alter the stress regime in both the Carboniferous bedrock and in the overburden. In this context, upward drillings are regarded to be preferential pathways for flowable overburden material, whereas downward drillings are most likely not affected by mine water rise.

Keeping the mine water level at the present state by pumping would at least preserve the status quo.

- Groundwater quality (WG 5.2.4)

Significant changes of the groundwater quality in the overburden cannot be excluded for a wider area of the mines southeast of the Maurits mine (see Subsection 4.4). This might be a significant threat for groundwater extraction in this area.

Keeping the mine water level at the present state by pumping would safely prevent a change of groundwater quality in the overburden.

- Groundwater quantity (WG 5.2.5)

Wetting at the ground surface due to rising groundwater levels in the near-surface underground cannot be excluded for several valley locations within the

mining districts, including the Maurits mine (see Subsection 4.5). This might be a local threat for buildings.

Keeping the mine water level at the present state by pumping would safely prevent wetting in the potential impact areas.

- Mine gas (WG 5.2.6)

Rising mine water will decrease the further release of mine gas from the additional flooded mine workings. Therefore, concerning the degassing of unflooded mined areas, pumping at the present level would maintain the current risk level; hence, the measure would be counterproductive.

- Seismic activity (WG 5.2.7)

Seismic activity might be induced by the load changes caused by rising mine water, resulting in a change of stress conditions at a tectonic fault. Overall, the risk is regarded to be low and no change of the seismic risk due to rising mine water is expected for South Limburg.

Furthermore, the additional load that could be prevented by stabilising the mine water level at the present state (about 40 m) is marginal considering the rise of mine water levels that has already happened in the mines. Lowering the mine water level would result in additional sudden stress changes which have to be regarded as more unfavourable than a further rise of the mine water level.

Overall, protective pumping would be of primary use for the prevention of impacts by differential ground heave, changes in groundwater quality in the overburden, and wetting at the surface in certain locations within the mining district.

For a stabilisation of the mine water level in the whole mining district (considering ground heave and wetting), at least two locations for pumping are necessary: one in the Maurits mine and the other in the southeastern mines.

The only shaft which is prepared for installing a pump is the Beerenbosch II shaft (Domaniale), in Kerkrade. According to the experience of protective pumping in the 1980s (see Section 3), pumping at this location would be sufficient to stabilise the mine water level in the southeastern and central mines including the Emma mine. The pumping will also influence the further development of the mine water level on the adjacent German territory.

In the Maurits mine, a new location must be found to create the possibility for pumping the mine water, as the shafts are filled with concrete. Therefore, a new well must be built on the level of the mine workings, at a depth of about 300 to 350 m.

The amount of mine water that would have to be pumped to stabilise the mine water level can be estimated to be about 2 to 3 m³/min at the Beerenbosch II shaft (Kerkrade). For the Maurits mine no information is available as a basis for a prognosis of the amount of mine water that would have to be pumped to stabilise the mine water level.

For the Beerenbosch II shaft, it is known from the pumping in the 1980s that the quality of the extracted mine water is very poor (ROSNER, 2011). In the 1980s the quality of the extracted water was characterised by an electrical conductivity of about 10.000 µS/cm, chloride-concentrations of about 3.000 mg/l, and quite high iron-concentrations of about 12 mg/l. The high mineralisation was mainly induced by the influence of ascending thermal water from the Oranje Nassau I-South concession; it cannot be excluded that the inflow of these waters will be reactivated by long-term active pumping. This means that the extracted mine water must be treated before discharging to the river Wurm, meaning additional costs for an appropriate infrastructure, treatment, and costs for the disposal of the remaining sludge - forever.

This scenario would basically also apply if pumping were to be executed at another location, e.g. in the Emma or Oranje Nassau mines, installing a new well, or using wells from the mine water project in Heerlen.

From the mine Maurits mine, it is known that the mineralisation of the mine water was also comparatively high, with chloride-concentrations of about 3.000 mg/l (ROSNER, 2011). Therefore, it cannot be excluded that the extracted water has to be treated before discharging to a river here as well.

At present, the threats from future rising mine water are quite hypothetical, based on simplified models of the groundwater situation and the underground configuration along the main tectonic faults. The potential for a concrete impact on surface or groundwater is restricted. In particular, concrete monitoring data about the quality and development of groundwater quality in the deeper groundwater reservoirs of the overburden are not available. Therefore, a restrictive measure such as perpetual pumping would be disproportional at the present time, considering the costs and impacts that the pumping itself would produce.

Nevertheless, it makes sense to keep this measure in reserve in case there is a further verification of the impact potential based on a future detailed monitoring and an improved prognosis based on a more detailed groundwater model.

5.2.2 Reactivation of historic dewatering galleries discharging to the river Wurm

In the early times of the coal mining in the Wurm river area, the mines were dewatered by galleries discharging into the river Wurm. On German territory, several of these old partly broken galleries were reactivated in the 1990s to limit the rise of the mine water to the level of these galleries resp. to the level of the river



Wurm; further galleries were intended to be reactivated before the mine water level will reach the level of the river Wurm. These measures were taken to prevent the flooding of the numerous old shafts of the near-surface mining which are mostly located above the level of the main dewatering galleries discharging into the river Wurm. Furthermore, flooding of the historical near-surface mine workings located close to the top of the Carboniferous should be prevented, so as not to increase the risk of sinkholes.

According to the prognosis for the future rise of the mine water in the South Limburg area, the level of the historic dewatering galleries discharging into the river Wurm will not be reached. This applies even for the worst case scenario (maximum level about 110 mNAP). Therefore, a reactivation of these dewatering galleries will not be productive for the area of historic mining on Dutch territory.

6 Integrated Bow-Tie-Analysis

This section describes the development and the results of the integrated Bow-Tie-Analysis. The section is divided into five subsections. Subsection 6.1 explains the approach used for the integrated Bow-Tie-Analysis. Subsection 6.2 describes the calculation of the risk factor. Subsection 6.3 goes into the usefulness of the different prevention controls. Subsection 6.4 describes the cost estimation, and Subsection 6.5 shows the effectiveness of the different prevention controls. Based on the discussion about the effectiveness of the single prevention controls, a prioritising plan for monitoring and measures is delivered in Section 7.

6.1 Approach

Based on the single Bow-Ties elaborated for the different after-effects/Top Events by each working group (Section 4; Appendix 1), an integrated model was used to give an insight into the most effective controls. The integrated model is a way to prioritise the different controls according to their effectiveness and the severity of the threat. This prioritising is done by carrying out the following analyses in turn, in order to determine:

- Which Top Event has the highest probability to occur, based on expert judgement.
- How severe/significant is the impact in case of a Top Event.
- What measures can be taken to directly prevent the occurrence of a Top Event or reduce the probability.
- What measures can be taken to indirectly reduce the probability of the occurrence of a Top Event.

Based on this analysis the *RISK FACTOR* and *USEFULNESS* of the measures can be determined, and an order of priority can be given to the different measures. This

is further elaborated in Subsection 6.2 and Subsection 6.3. Cost estimation is made of almost all prevention controls and some fundamental recovery controls. These estimated costs, in combination with the *USEFULNESS* of the prevention controls, provide an indication of the *EFFECTIVENESS* of the different measures. This is further elaborated in Subsection 6.4.

Note that the analyses have only been carried out for the prevention controls of the Bow-Ties (controls which are presented on the left side of the Bow-Tie-diagrams). The present study gives no priority to the ranking of the recovery controls. The different working groups have indicated that it is not worthwhile to prioritise the recovery controls (these controls are designed to reduce or prevent the undesirable effects after a Top Event has occurred).

A major reason to exclude the recovery controls is that most of these controls are “no regret”-measures, which are known to be useful and relatively cost effective and therefore should be performed in all cases. The different working groups established that it is practically impossible to specify beforehand which escalation controls are required. These escalation controls are extremely dependent on the scale of the event and the local conditions.

6.2 Risk Factor

First the *RISK FACTOR* of each Bow-Tie is calculated using the formula:

$$\text{RISK FACTOR} = \text{Probability of occurrence} \times \text{significance of consequence}$$

- The probability that a Top Event occurs is estimated using expert judgement using the following probability figures: 20 %, 40 %, 60 %, 80 %, and 100 %.



- The score to indicate the significance of the consequence is estimated using expert judgement, taking into account the most undesirable consequence. The possible scores used are:
 - 1: small effect, no damage or injuries to be expected;
 - 5: medium effect, repairable damage or injuries to be expected;
 - 10: large effect, major damage or lethal injuries to be expected.

Tab. 3 shows the comparative *RISK FACTORS* for the different Top Events described in the seven single Bow-Ties (see Appendix 1).

Tab. 3: Comparative “Risk factors” for the Top Events described in the single Bow-Ties

Working group	Top Event	Probability of occurrence		Significance of consequence		Risk factor [1]
		figure [%]	description	score [1]	description	
5.2.1 / ground movements	differential ground heave	40	medium	5	Repairable damage to buildings and infrastructure is the highest expected impact due to differential ground heave	2
5.2.2 (h) / historical mine shafts	collapse / sink-hole / subsidence	60	more likely than not	10	Lethal injuries are a possibility if a historical shaft collapses	6
5.2.2 (i) - industrial mine shafts	collapse / sink-hole / subsidence	60	more likely than not	10	Lethal injuries are a possibility if an industrial shaft collapses	6
5.2.3 - near-surface mining	collapse / sink-hole / subsidence	40	medium	10	Lethal injuries are a possibility if a near-surface mining void collapses	4
5.2.4 / groundwater quality	changing quality of deep groundwater	40	medium	10	Non-recoverable degradation of water quality is a possibility	4
5.2.5 / groundwater quantity	wetting stream valleys	20	small	1	Wet cellars are the only expected damage	0,2
5.2.6 - mine gas	gas trapping in building	20	small	10	Lethal injuries due to explosions are a possibility if gas is trapped in a building	2
5.2.7 - small earthquakes	triggered earthquake	20	small	5	Repairable damage to buildings and infrastructure is the highest expected impact due to (small) seismic activity	1

6.3 Usefulness of the controls

This subsection describes the reasoning behind the result of the *USEFULNESS* of the prevention controls. The *USEFULNESS* of each prevention control is calculated using the formula:

$$USEFULNESS \text{ prevention control} = RISK \text{ FACTOR} \times \text{effect prevention control}$$

Within this formula the *RISK FACTOR* according to the previous paragraph is used. The effect of the prevention controls is ranked according to:

- 1: minor effect - will not directly reduce the chance of a Top Event;
- 2: medium effect - will reduce the chance of a Top Event or may give insight for other measures;
- 3: large effect - will eliminate the chance of a Top Event or provides essential information for other measures.

The results for the single prevention controls are listed in Appendix 2 - Table 1. For example, the *USEFULNESS* of a prevention control is 6 if it scores a 3 with Top Event 5.2.6 ($3 \times 2 = 6$). The same control can have a higher *USEFULNESS* if it scores a 2 with Top Event 5.2.4 ($2 \times 4 = 8$).

The *USEFULNESS* is applied for the highest overall score. The prevention controls are divided into three groups with different *USEFULNESS* scores:

- group 1 - prevention controls with the highest score (18 to 12 points)
- group 2 - prevention controls with an average score (11 to 6 points)
- group 3 - prevention controls with a lower score (5 to 0 points).

An overview of the ranking for each control effect and the total *USEFULNESS* score is presented in Appendix 2 - Table 2.



6.3.1 Prevention controls group 1 (18 - 12 points)

The group 1 contains the prevention controls with the highest overall scores but also the highest total score due to the frequency of their entries in the single Bow-Ties.

This group contains most of the basic monitoring measures:

- monitoring groundwater level;
- monitoring mine water level;
- monitoring groundwater quality.

All these monitoring measures have been indicated as effective, because they are needed to give insight into the feasibility of other measures. Without these monitoring measures it is almost impossible to indicate which other prevention and recovery controls will be effective.

Other prevention controls within this group are measures which almost or even totally prevent the Top Event from occurring. These measures are:

- remediation measures;
- stabilisation of underground mine voids and the rock roof.

The development of a sinkhole at a historical or industrial mine shaft or above the near-surface mining voids is prevented as far as possible by activating these prevention controls.

Furthermore, there are some measures that can reduce the risk of a sinkhole above a shaft significantly by reducing the load or limiting the influx of seepage water as long as the shaft is not remediated.



6.3.2 Prevention controls group 2 (11 - 6 points)

This group contains monitoring measures for industrial shafts, ground heave, and mine gas:

- monitoring industrial shafts;
- site inspections (historical shafts);
- monitoring ground heave;
- measurements for mine gas.

The monitoring of industrial shafts is considered to be a necessary and important measure to prevent the development of severe damage in the impact areas of the industrial shafts. Potential alterations in the backfill column - commonly a triggering mechanism for further damage - will most likely reflect themselves at the surface of the backfill column. Hence, monitoring measures should, at least, be applied for the backfill column.

Site inspections at historical shafts are an important measure to prevent the development of severe damage in an early state of the development of a sinkhole, but they cannot prevent the Top Event itself, and are therefore rated in the second group. Site inspections should be a temporal measure as long as the shafts are not remediated.

Monitoring of ground heave and measurements of mine gas are basic monitoring controls for the future risk assessment of these after-effects. But they are rated in the second group instead of in the first group, as these monitoring measures are related to Top Events with a risk factor of 2, and are therefore regarded less important than prevention controls for Top Events with a high probability of occurring and a large impact.



Besides the monitoring measures, there are measures in group 2, which should decrease the risk of damage due to degassing mine gas. People should be aware of the risk if they drill or build houses in potential impact areas, and take the necessary precautions. In problematic zones, ducts in buildings should be gas tight to prevent the migration of mine gas into the buildings.

6.3.3 Prevention controls group 3 (5 - 0 points)

Group 3 comprises measures that might help to prevent a Top Event or the severity of the impact from impacts on the groundwater (WG 5.2.4 / WG 5.2.5):

- regulation of groundwater extraction in potential impact area Ia/b;
- change configuration of wells in potential impact area Ia/b;
- restrictions in the catchment area.

Regulating and changing groundwater extraction only makes sense if more concrete findings about the location and the severity of the threats are available. Restrictions in the catchment area regarding, for instance, new buildings might be an appropriate measure for further planning to prevent damage due to wetting, but will have no influence on the Top Event.

Furthermore, there are measures that should provide additional information for a better understanding of the hydraulic system and an early detection of potential threats:

- research of hydrological connections in the potential impact areas;
- development of an early warning system;
- geo-hydraulic research.

The measures in group 3 are rated with a lower usefulness due to their comparatively restricted influence on the Top Event, on the one hand, and their compara-

tively low risk factor for the potential impacts due to wetting stream valleys (WG 5.2.5).

6.3.4 Group 4 - “preventive recovery controls”

In addition to the prevention controls, there are numerous preventive measures that are listed under recovery controls due to the systematic of the Bow-Tie but should also be considered in the further planning for monitoring and measures (Section 7). Therefore, an additional group 4 with “preventive recovery controls” has been created (Appendix 2 - Table 3).

This group comprises measures that have no influence on the Top Event but which will communicate the problems to the public and avoid damage by anticipating the potential problems at an early stage in the further planning of infrastructure and buildings. The usefulness of these measures is rated on the basis of expert judgement according to the principles described above. Most of the measures are assigned to usefulness group 1 due to their essential nature for the handling of the future impact potential and comprise:

- awareness-raising,
- communication,
- detailed monitoring of three potential impact areas (WG 5.2.1),
- regional development planning,
- adapted site investigation,
- adapted construction/construction guidelines.

Two of the measures - the pilot research projects Geleen (WG 5.2.1) and Heerlen (WG 5.2.3) - have already been assigned due to their crucial importance for the assessment of the impact potential in the frame of the ongoing study.

The “inventory of sensitive structures in the three potential impact areas” is assigned to usefulness group 2 due to the lower risk factor of the respective Top Event (WG 5.2.1).

Further measures are assigned to usefulness group 3 due to their more theoretical and experimental approach to the problems and comprise:

- development of an early warning system for the detection of sinkholes;
- development of an early warning system for the detection of a change in groundwater quality;
- seismic study and monitoring.

6.4 Cost estimation

For the different prevention controls and some of the basic recovery controls (as listed in Appendix 2 - Table 3) cost estimations were provided by the individual working groups. These cost estimations contain the initial investment costs and the annual costs for five years. The cost estimations of each working group are presented in Appendix 3. The costs are of importance for the determination of the *EFFECTIVENESS*, as described in the next paragraph.

For further evaluation in a decision matrix, the costs for the different prevention controls have been divided into five groups; investment costs and operational costs for a five-year period are considered separately. The respective limiting amounts for the different groups are listed in Tab. 4.

For monitoring the ground movements, monitoring measures are divided into three categories with different accuracy and costs. Measures of first-order priority are regarded as obligatory for further monitoring. In this monitoring category, extensive area monitoring will be restricted to the evaluation of medium-



resolution satellite data, with the existing GNSS stations as the terrestrial reference. Levelling benchmarks should be maintained. The detailed monitoring of the potential impact areas will be limited to a detailed levelling of benchmarks along a few representative lines (levelling profiles).

Tab. 4: Cost groups for prevention controls

Cost group	Investment [€] excl. VAT	Operational costs for 5 years [€] excl. VAT
1	≤80.000	≤10.000
2	> 80.000 - 1.200.000	> 10.000 - 150.000
3	> 1.200.000 - 8.000.000	> 150.000 - 1.000.000
4	> 8.000.000 - 20.000.000	> 1.000.000 - 2.500.000
5	> 20.000.000	> 2.500.000

A further intensification of the monitoring measures is dependent on the needs that might arise in the course of the further development of the ground movements. For more extensive monitoring of the potential impact areas, the evaluation of high resolution satellite data can be added (second-order priority). The highest accuracy can be achieved by evaluating different InSAR satellite sights (ascending and descending) and combining it with both data from additional GNSS stations and levelling as the terrestrial reference (third-order priority).

The costs for the remediation of shafts and the near-surface underground voids are extrapolated from the experience in the Herzogenrath area (Germany). Costs for the monitoring of mine gas are based on the experience in the Ruhrgebiet area (Germany).

Costs for the “preventive” recovery controls (Group 4) are listed in Appendix 2 - Table 3, according to the cost groups in Tab. 4. The respective costs are included



in Appendix 3 for some of these measures; for the measures not listed in Appendix 3, the costs were estimated roughly and classified.

6.5 Effectiveness of controls

This subsection describes the reasoning behind the results of the *EFFECTIVENESS* of the prevention controls. The *USEFULNESS* in combination with the cost estimation for the prevention controls provides an indication of the *EFFECTIVENESS* of each measure. The prevention controls are listed according to the different *USEFULNESS* groups, with the respective costs in Appendix 2 - Table 4. The decision framework is depicted in Fig. 30.

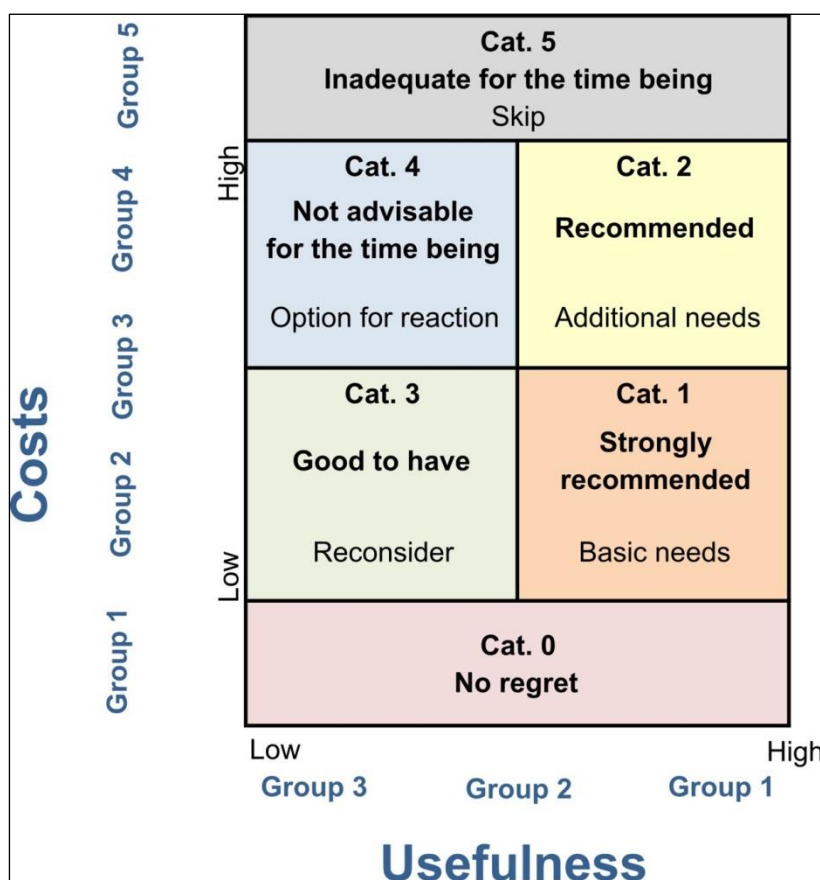


Fig. 30: Decision matrix for the classification of the *EFFECTIVENESS*, according to six categories (Cat. 0 to Cat. 5)

The following categories have been considered:

Cat. 0: No regret: Important measures for the further handling of the potential impacts from rising mine water with comparably low costs.

Cat. 0 comprises measures that serve awareness-raising and an early regard for the potential impacts in the future planning of buildings, groundwater extraction, etc. These are mostly administrative tasks which are not rated in terms of costs here (cost group 1).

Also assigned to this category are the temporal measures to reduce the risk of sinkholes above historical mine shafts (e.g. reduce load on shaft head and influx of water). First of all, it is an administrative task to provide regulations for the respective potential impact areas.

Cat. 1: Strongly recommended: Basic needs for monitoring and remediation measures to handle severe potential risks.

Cat. 1 comprises the monitoring of mine water and groundwater as a basic need for the registration of the most important immediate effects of rising mine water. Furthermore, remediation measures at six industrial shafts are considered to be a basic need.

Cat. 2: Recommended: Additional needs for a complete survey of the after-effects.

In Cat. 2 remediation measures at historic shafts and the monitoring of ground movements are listed. These remediation measures are listed in Cat. 2 and not in Cat. 1 due to their high investment costs. Nevertheless, these measures are considered as necessary actions to guarantee people's safety.

The monitoring of ground movements is listed in Cat. 2 due to the lower risk factor of the respective Top Event. Nevertheless, this belongs to the necessary tasks for the survey of the effects from the rise of mine water.



Cat. 3: Good to have: Reconsider on the basis of the first results of the extended monitoring.

Measures that provide a better understanding of the after-effects from rising mine water with respect to the impacts on the groundwater and the ground movements (second-order priority).

Cat. 4: Not advisable for the time being: Optional as a reaction on first suspicion.

Measures that might be necessary if suspicious changes (e.g. of groundwater quality or ground movements) become obvious on the basis of further investigations and monitoring.

These comprise regulations of groundwater extractions or change of well configurations to prevent a further development of quality change in deep groundwater and detailed monitoring of ground movements (third-order priority).

Cat. 5: Inadequate for the time being: Skip.

Measures that are too expensive to provide an adequate contribution to the prevention of the Top Event or combined with other severe risks.

The remediation of all the near-surface mining voids is the only measure to prevent sinkholes above these historic mines. But costs and technical expenses are much too high to make it a feasible measure. Therefore, such comprehensive preventive remediation of historic mining voids is also not an option in other mining regions.

Considering the *EFFECTIVENESS* this measure can be regarded comparable to a perpetual pumping of mine water as discussed in Section 5. It is effective but there are other reasons that make it unfeasible.

Based on this classification the measures assigned to categories 0 to 3 above will be considered for further action.

7 Catalogue of measures and monitoring plan

The measures and monitoring that are advised on the basis of the integrated Bow-Tie-Analysis for the future handling of the potential impacts from mining relicts and rising mine water are listed in Plan 8. This plan for monitoring and measures comprises the measures and monitoring assigned to Cat.0 to Cat.2 (*EFFECTIVENESS*), according to Section 6 with a time schedule for the first five years. The location of the monitoring devices (levelling profiles, piezometer) and the shafts where monitoring and remediation measures are advised are shown in Plan 9.

- Communication, awareness-raising, preventive regulations

The first actions comprise providing information for the people and the local authorities that are handling the construction and safety items (e.g. communication, awareness-raising). Private planners, architects, and drilling companies are important multipliers which should be informed. The results of the project must be communicated to the local people and authorities and incorporated in their planning tools.

With this information, regulations for buildings, site investigations, and drilling should be formulated in the short-term by the local authorities.

- Installation of monitoring devices

Furthermore, preparatory measures have to be initiated to establish an appropriate monitoring system (e.g. installing piezometers, levelling benchmarks, provision of instruments for gas measurements).

For the monitoring of the potential impact areas for differential ground heave in Geleen, Brunssum and Eygelshoven (see Plan 1), six levelling profiles of about



0,75 to 1,5 km are advised (Plan 9). New benchmarks have to be installed along these profiles about 25 m from each other.

For groundwater monitoring, the drilling of seven additional piezometers is advised. A proposal for the location of these piezometers is depicted in Plan 9.

The monitoring of the mine water level will be continued in the three shafts that are already being monitored by the Province of Limburg (Julia, shaft II / Wilhelmina, shaft I/ Oranje Nassau I, shaft II; see Plan 9). In addition, the shafts of the Domaniale mine (Beerenbosch II, Willem II; Plan 9) should be included; these shafts are measured by the German mine company EBV GmbH; the data could be obtained from EBV GmbH by data exchange.

As a basis for the site inspections of the historical shafts, an inventory of the local situation should be established. For the monitoring of 30 industrial shafts (see Plan 9), the shaft heads have to be accessible and feature a manhole; monitoring devices such as levelling staffs have to be installed.

The monitoring of mine gas should focus on buildings that are located within “Gas-emission-protection-zones”. For these buildings, first, an exterior assessment of the structural conditions of the building has to be conducted. If relevant cracks or fissures in the walls or the bottom slabs of some buildings are observed, these partly damaged buildings are the main target point for monitoring measures. A measurement of the current state of mine gas is to be conducted. For the monitoring of mine gas, the installation of stationary measuring devices is not considered to be necessary. The monitoring can be conducted using portable measuring devices.

- Monitoring

In a second step, the advised monitoring measures must be established and carried out regularly.

It is advised that shaft inspections are performed at quarterly intervals for the historic shafts. On the basis of a shaft inventory, the inspection intervals should be fixed according to the sensitivity of the single locations. Monitoring at industrial shafts is advised yearly for four shafts and quarterly for 26 shafts.

The levelling profiles that serve to detect zones with significant differential ground heave are advised to half-yearly updates.

The periodical evaluation of medium-resolution InSAR-data serves as a basis for the detection of regional trends. As an absolute reference for detrending the InSAR time series, GNSS measurements have to be made. The currently existing GNSS stations should continue to operate. The measurements are the main basis for the assessment of the regional impact on the surface and a verification of the prognosis. The evaluation should cover the mining region plus a buffer zone of 5 km. The evaluation of the data should be done once a year.

For the monitoring of the mine water level, the shafts measured by the province are equipped with measurement devices (data loggers) for continuous measurements. The Domaniale shafts are measured by EBV GmbH by hand at intervals of about 2-months for the time being; these intervals are considered to be sufficient for the time being in order to meet the needs of the Dutch monitoring system.

The piezometers for groundwater monitoring will be supplied with data loggers for continuous measurements of the groundwater levels. Analyses of the groundwater are advised once a year in six selected wells.

For the buildings that were identified as being affected by the emission of mine gas, a semi-annual monitoring of the constituents methane, oxygen, and carbon dioxide should be performed. The monitoring intervals might vary depending on possible structural modifications of the buildings. During certain construction measures within the areas that are potentially affected by the emission of mine gas, gas monitoring has to be performed continuously. Further mine gas monitoring should be integrated with the regular inspection of sewage systems in the threatened area.

The results of the monitoring should be summarised in yearly reports with an updated risk assessment and proposals for further monitoring and measures. It is advised to include an assessment of data from other activities that influence the mine water level, such as the mine water project in Heerlen or any measures on the adjacent Belgian or German territory in, respectively, Herzogenrath and Würselen.

- Shaft remediation

For the remediation of the industrial and historic shafts an action plan with priorities and a time schedule has to be established when the necessary financial means are provided. The remediation of the historic shafts will be a long-term task independent of the future mine water rise.



8 Summary

Within the scope of the project a comprehensive inventory and risk analysis of the after-effects from former coal mining in South Limburg has been elaborated. The Top Events that might lead to damage at the surface or to the groundwater have been identified and rated according to the remaining risk that is expected for the future. Table 5 provides an overview of the identified Top Events and the specified risks rated by a risk factor (6 = highest risk), classified according to their appearance in each municipality of the South Limburg mining district is.

Tab. 5: Overview of the identified after-effects and resulting risks in the municipalities of the South Limburg mining district

Municipality	After-effect / Top Event						
	WG 5.2.1 - ground movements	WG 5.2.2 - mine shafts	WG 5.2.3 - near-surface mining	WG 5.2.4 - groundwater quality	WG 5.2.5 - groundwater quantity	WG 5.2.6 - mine gas	WG 5.2.7 - small earthquakes
	Differential ground heave	Collapse/sinkhole/subsidence above mine shafts	Collapse/sinkhole/subsidence near surface mining*	Changing quality of deep groundwater	Wetting stream valleys	Gas trapping in building	Triggered earthquake
Beek			X				
Brunssum	X	X	X	X			
Heerlen		X	X	X		X	
Kerkrade	X	X	X			X	
Landgraaf	X	X	X	X		X	
Nuth			X	X			
Onderbanken			X	X			
Schinnen	X	X	X	X	X		
Simpelveld			X				
Sittard-Geleen	X	X	X	X	X		
Stein	X		X		X		
Voerendaal			X	X			

Risk factors	6	2
	4	≤1

*including "Smaller mining relicts"

The investigations have shown that the risks from shafts or near-surface mining exist independent of the rising mine water, while the other risks very much depend on the extent and velocity of rising mine water.

Since the closure of the first mines in the 1960s, the mine water level has already risen substantially. Meanwhile, all mining voids in the northwestern and central part of the mining district have been flooded. But, mainly in the southwestern



area of the historic mining in Kerkrade, the mine water level has not yet reached the top of the Carboniferous. Based on a groundwater model, the final state of the mine water level is expected to rise no higher than 80 mNAP in Kerkrade, and about 40 mNAP in Stein (calculated for the most probable “average case”). The time it takes until this final state is reached is estimated to be at least 20 years from now.

According to the results of an integrated Bow-Tie-Analysis, the main potential risks arise from 59 historical shafts and from six industrial shafts; all these shafts are located in the municipality of Kerkrade. At these locations there is a general potential for the development of collapse/sinkhole or subsidence at the surface. This forms a threat to the integrity of buildings and infrastructure, as well as to health and even people’s lives.

This threat is mainly independent of the rising mine water, and the only way to handle it is the remediation of the shafts in the near future. The potential impacts from the shafts have to be considered by future planning at the surface.

Further industrial shafts are located in the municipalities of Brunssum, Heerlen, Landgraaf, Schinnen, and Sittard-Geleen; however, these shafts are considered to have a safety level that, in the moment, only requires a regular monitoring.

In the areas of near-surface mining, there is a further risk of the development of collapse/sinkhole or subsidence. This mainly concerns the historic mining area of Kerkrade. But, moreover, 26 locations of industrial mining near to the top of the Carboniferous bedrock are comparable to the situation that led to the sinkhole at ‘t Loon in Heerlen. For a more concrete assessment of the risks at such locations, a pilot project is ongoing in Heerlen. There, the probability of the occurrence of collapse/sinkhole is lower than at the mine shafts, and therefore the risk of this Top Event is rated lower.



Further significant risks arise from future ground movements and potential impacts on the groundwater due to the rising mine water.

Ground heave due to the rising mine water has already developed since the 1980s. Up until now ground heave up to a maximum of about 0,35 m has been observed. In the future a maximum of further 0,10 to 0,17 m is expected. As, to date, no significant damage or zones with differential ground heave have become obvious, the risk of the development of damage in the future is restricted. Three potential impact areas at the main tectonic fault zones of the mining district in Brunssum, Kerkrade, and Sittard-Geleen - and to a small extent in Landgraaf and Stein - have been identified, where damage to buildings or infrastructure due to differential ground heave cannot be excluded for the future. For the monitoring of the ground movements, a regional evaluation of satellite data (InSAR) is advised. In the potential impact areas, detailed levelling profiles should be installed and measured for the early detection of problematic zones.

Impacts on the quality of the deep groundwater are mainly expected in the area of the Emma mine (mainly at Brunssum, Heerlen, Schinnen, Nuth, and Onderbaken for the most probable “average case”). In the Emma mine the piezometric head of the mine water is expected to rise higher than the groundwater level in the limestone groundwater reservoir. Therefore, a change of groundwater quality due to ascending higher mineralised mine water cannot be excluded. A significant change of the groundwater quality might especially impair the groundwater extraction from the Cretaceous limestones. As the changes of groundwater quality that have been calculated with the groundwater model are of limited amounts, the risk is restricted as well. Nevertheless, due to the severity of the potential impact and the uncertainties of the groundwater model, this has to be regarded as an important risk for the future. To handle this risk and as a basis for a better risk assessment, additional piezometers and a comprehensive groundwater monitoring



are advised. In the frame of planning new groundwater extraction locations, this potential impact has to be considered. In case of significant changes in groundwater quality, a change of well configurations or even relocation might be suitable measures to take.

The only way to prevent further ground heave or impacts on the groundwater is to stop the rise of the mine water by pumping. This measure has been discussed but found inadequate considering the necessity for perpetual technical efforts for water treatment and the impacts on the river where the mine water has to be discharged, as well as the economic considerations and aspects of natural water management.

Minor impacts are expected due to ascending mine gas in the southeastern part of the mining district, where mine workings still are not flooded. The main problem arises from CO₂ which might lead to suffocation if trapped and accumulated in a cellar for example; methane is not a problem. It is advised to make people in the concerned area of Heerlen, Kerkrade and Landgraaf aware of the problem, and undertake gas monitoring at representative locations.

No significant risks are expected concerning wetting at the surface due to rising groundwater levels or the triggering of additional earthquakes due to the rising mine water. Wetting cannot be excluded in some valleys with high near-surface groundwater levels in the municipalities of Schinnen, Sittard-Geleen, and Stein (considering the most probable “average case”). However, the probability is low; but in case it happens and buildings are concerned, additional drainage could prevent damage. It is advised that this problem should be handled by appropriate monitoring of the groundwater level. This will help to detect problems early enough to be able to react properly.

Concerning the seismic situation, the investigations show that there is no change to the existing risk map of South Limburg due to rising mine water. Therefore, no specific action is necessary.

Overall, it can be stated that, to date, no significant impacts from rising mine water have been observed. For the future 40 years, the impacts due to rising mine water are expected to be restricted in terms of both location and severity. Differential ground heave might be a problem in three identified, quite restricted areas. Impacts on the groundwater are expected to be restricted as well, but it should be noted that the main threat to groundwater quality will appear in the final state of the mine water rise, when the mine water reaches its highest level. The most important risks arise from mine shafts. These risks are more or less independent from the future rise of the mine water.

As a result of the investigations, a comprehensive plan for measures and monitoring is delivered here as a basis for the future handling of the “Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg”.

Aachen / Deventer, 30 September 2016

Witteveen  **Bos**

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Ir. Michael Rauwers

IHS


Dr. Johannes Klünker

Dr. Peter Rosner

Dr.-Ing. Michael Heitfeld



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Appendix 1

**Na-ijlende gevolgen steenkolenwinning
Zuid-Limburg**

Summary report
with integrated Bow-Tie-Analysis

Bow-Ties of the single working groups

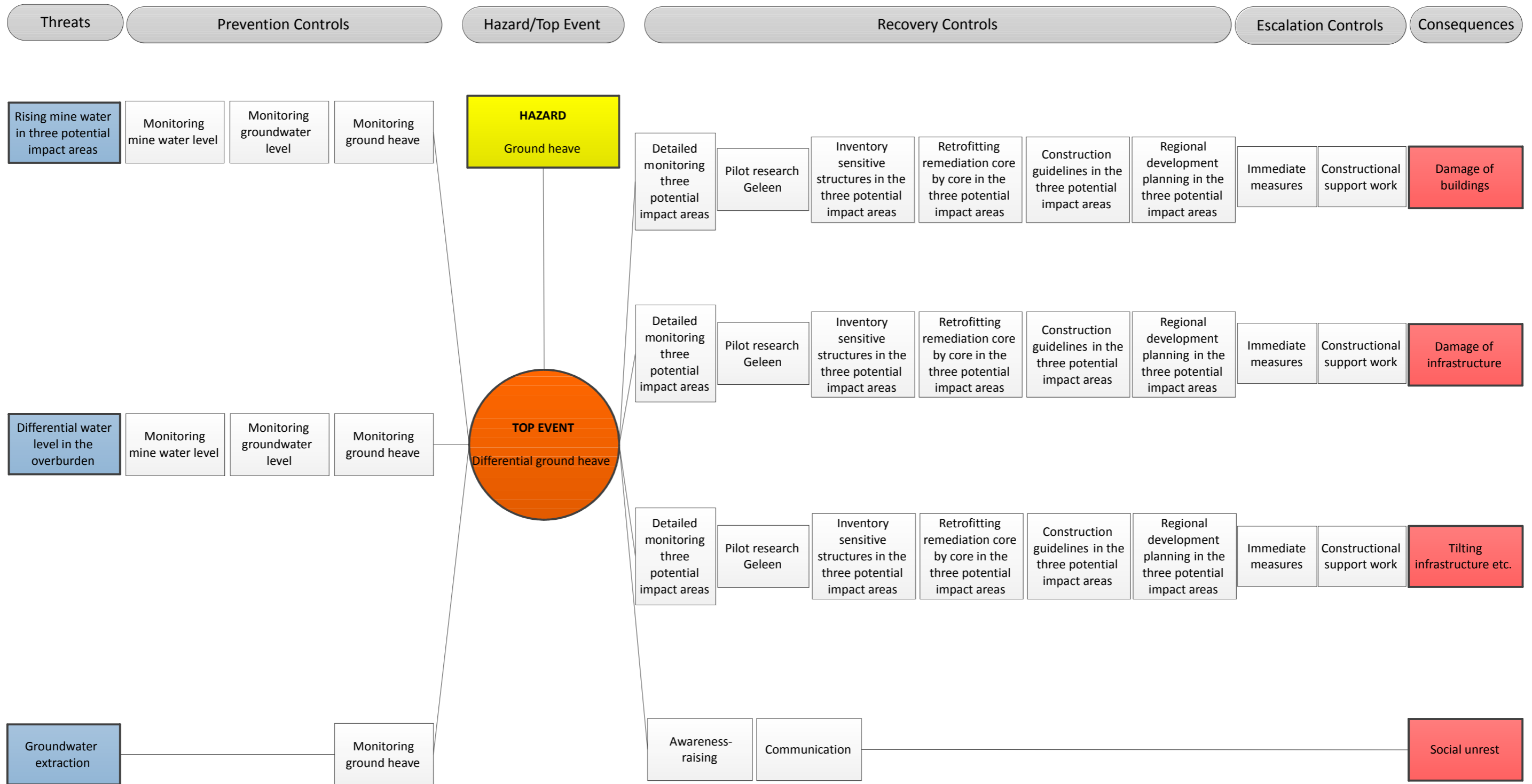
by

Projectgroup
"Na-ijlende gevolgen van de steenkolenwinning in
Zuid-Limburg"
(projectgroup GS-ZL)

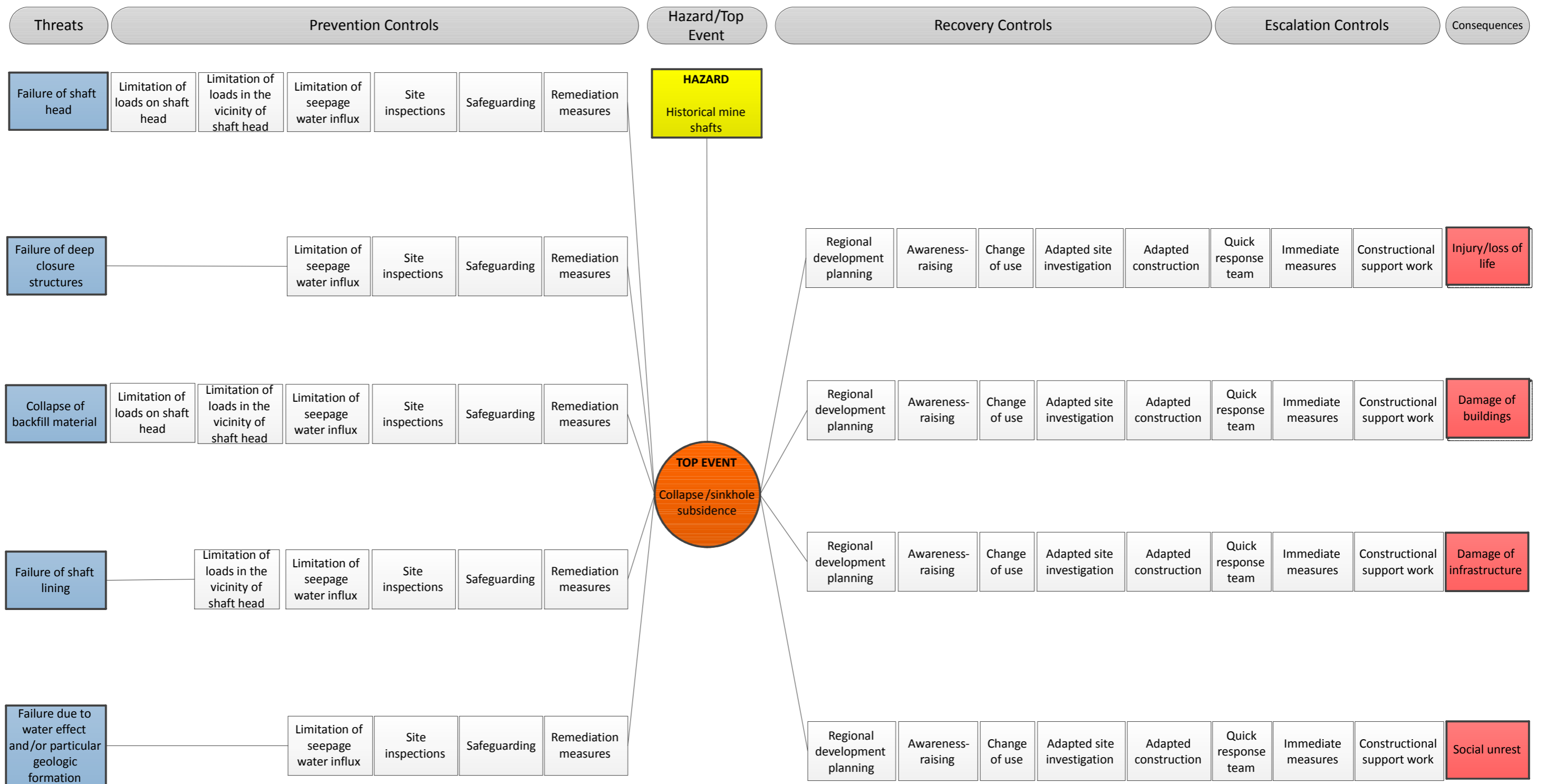
on behalf of
Ministerie van Economische Zaken - The Netherlands

Aachen (D) / Deventer (NL), 30.09.2016

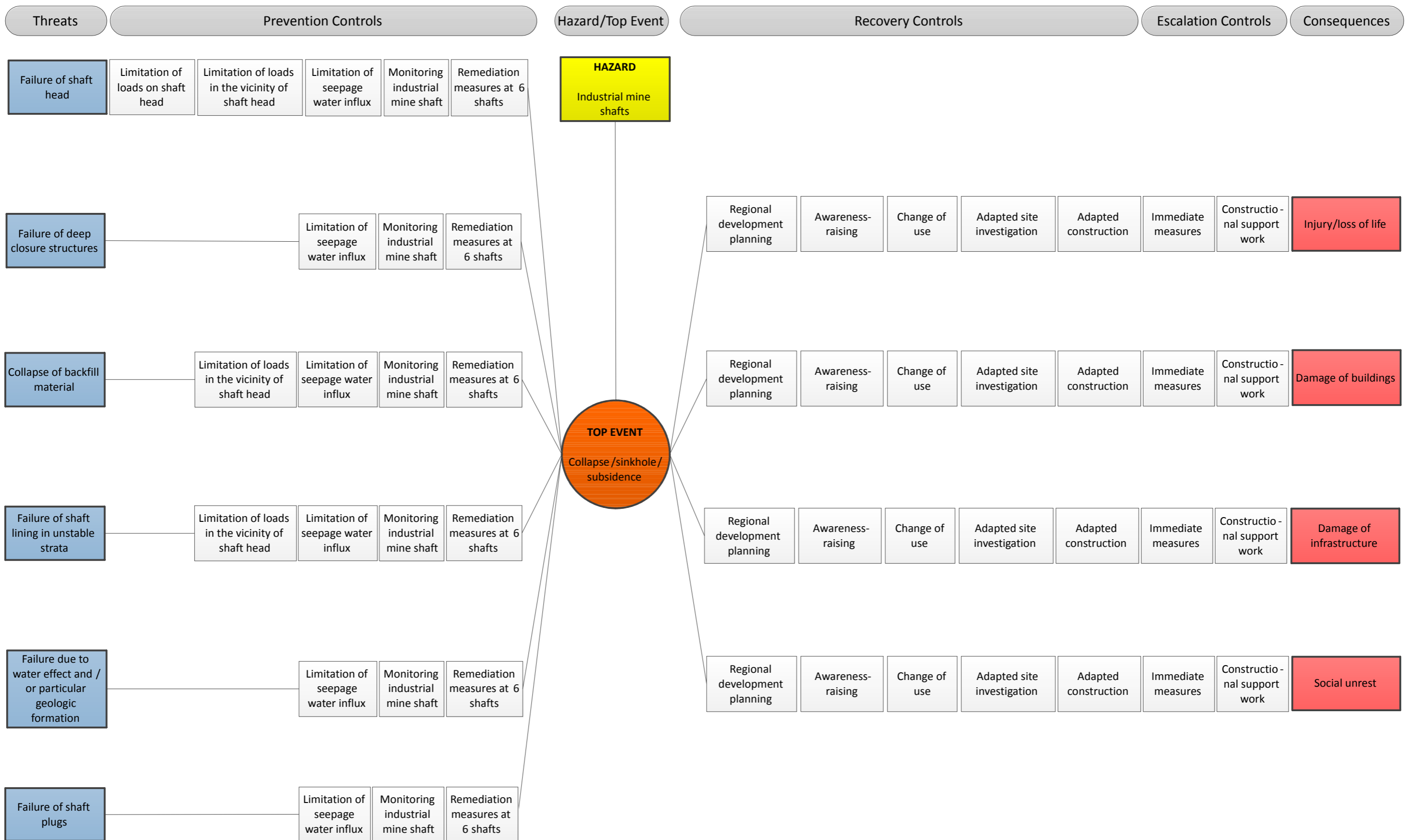
5.2.1 Ground movements



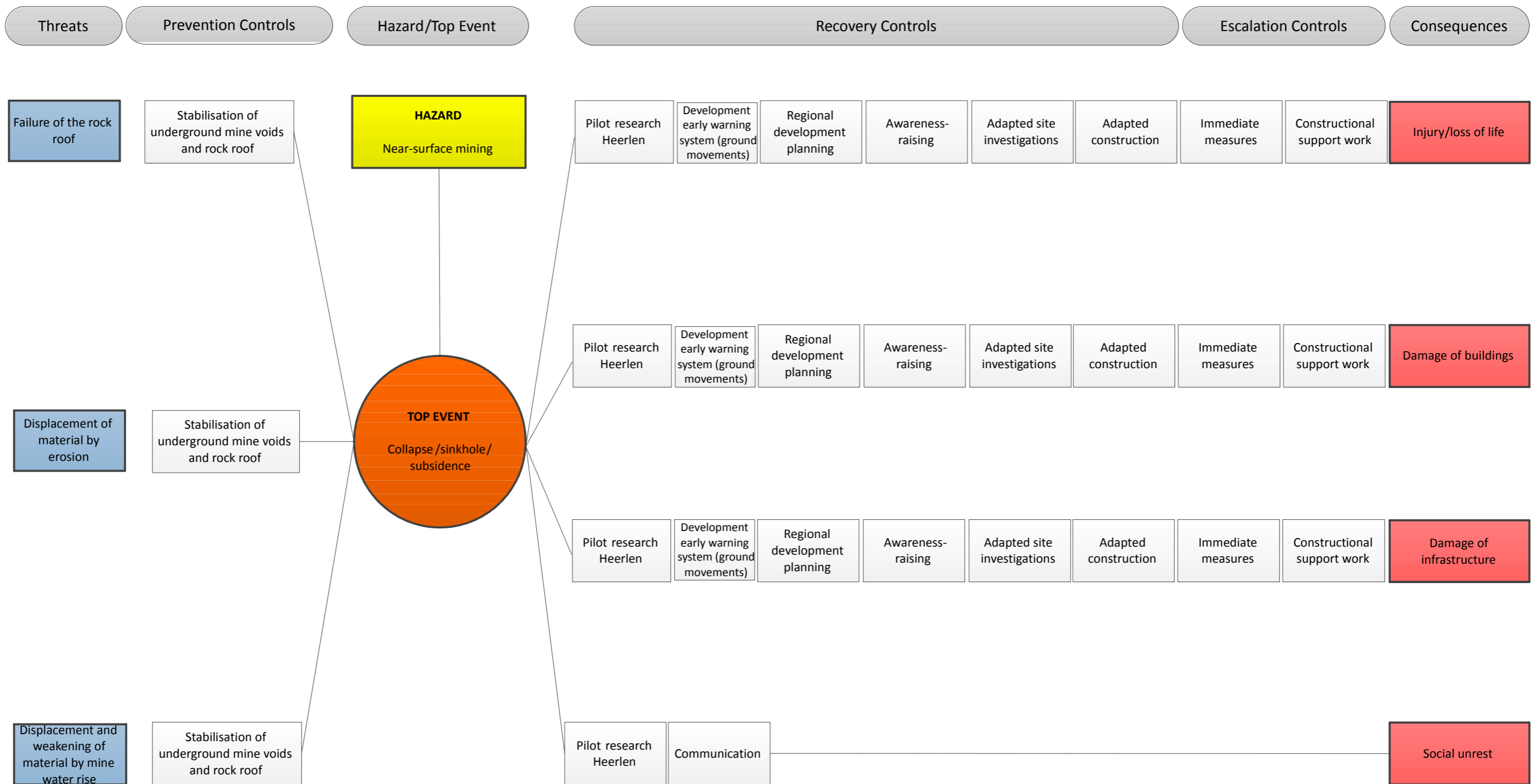
5.2.2 Mine shafts



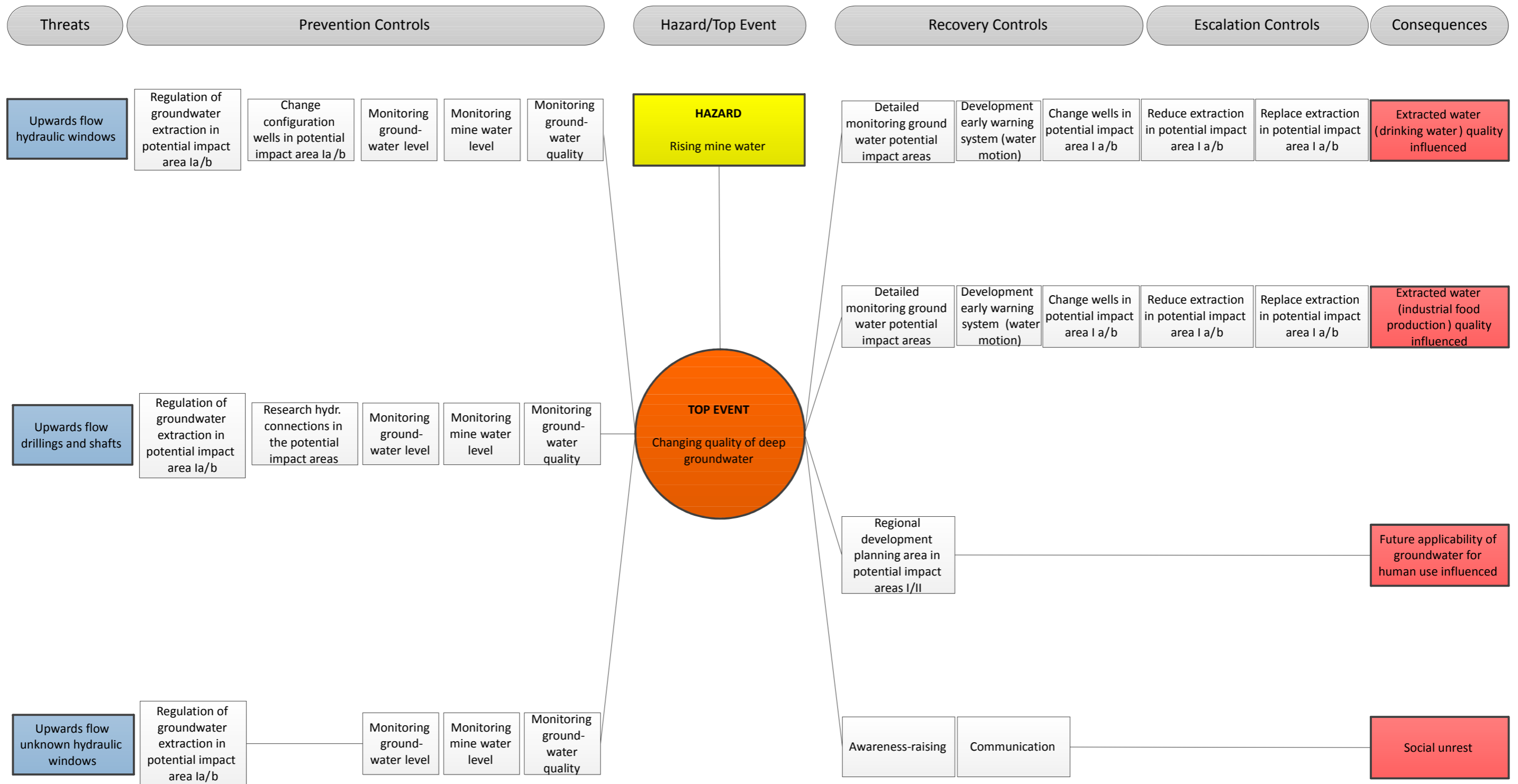
5.2.2 Mine shafts



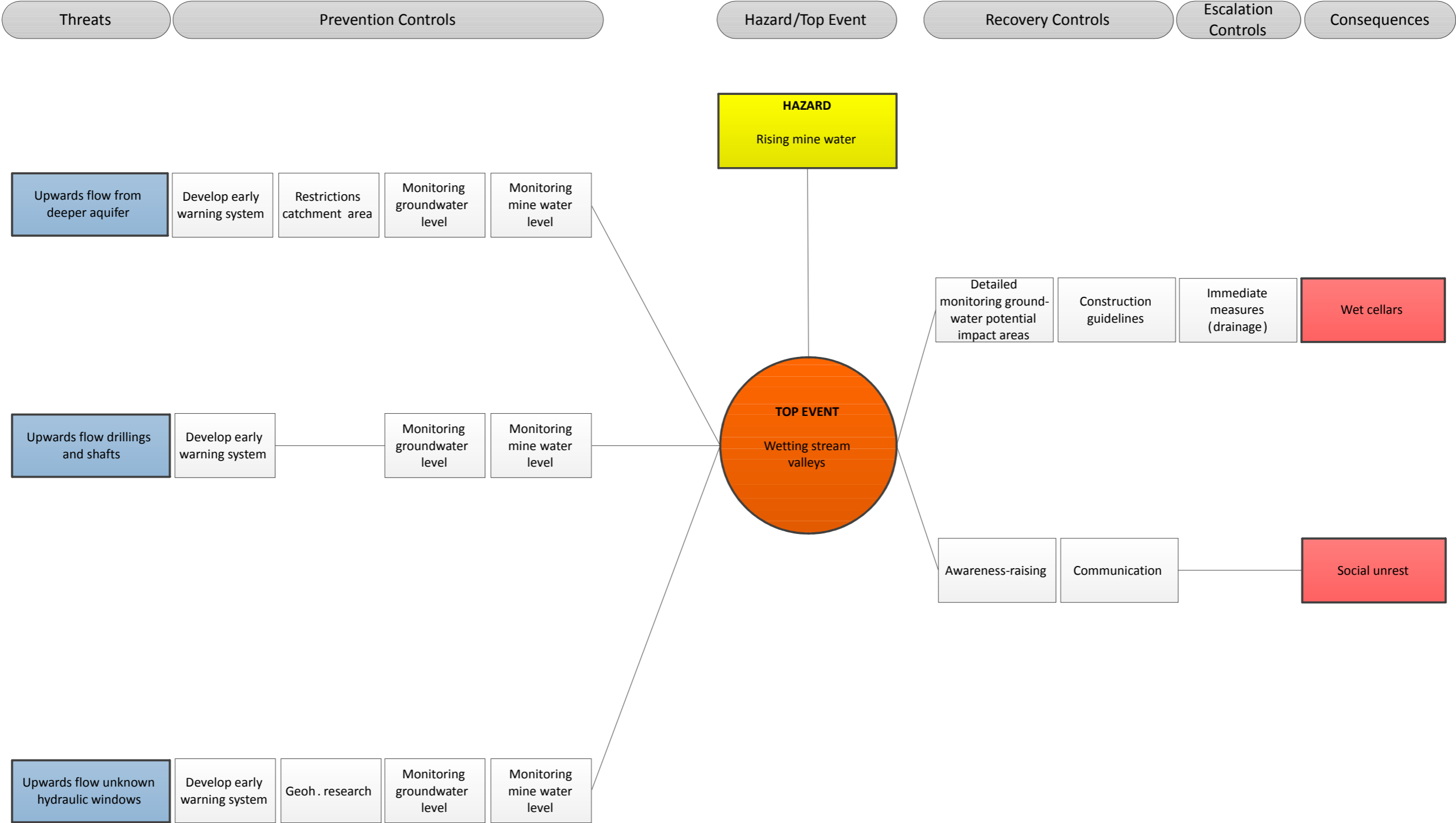
5.2.3 Near-surface mining



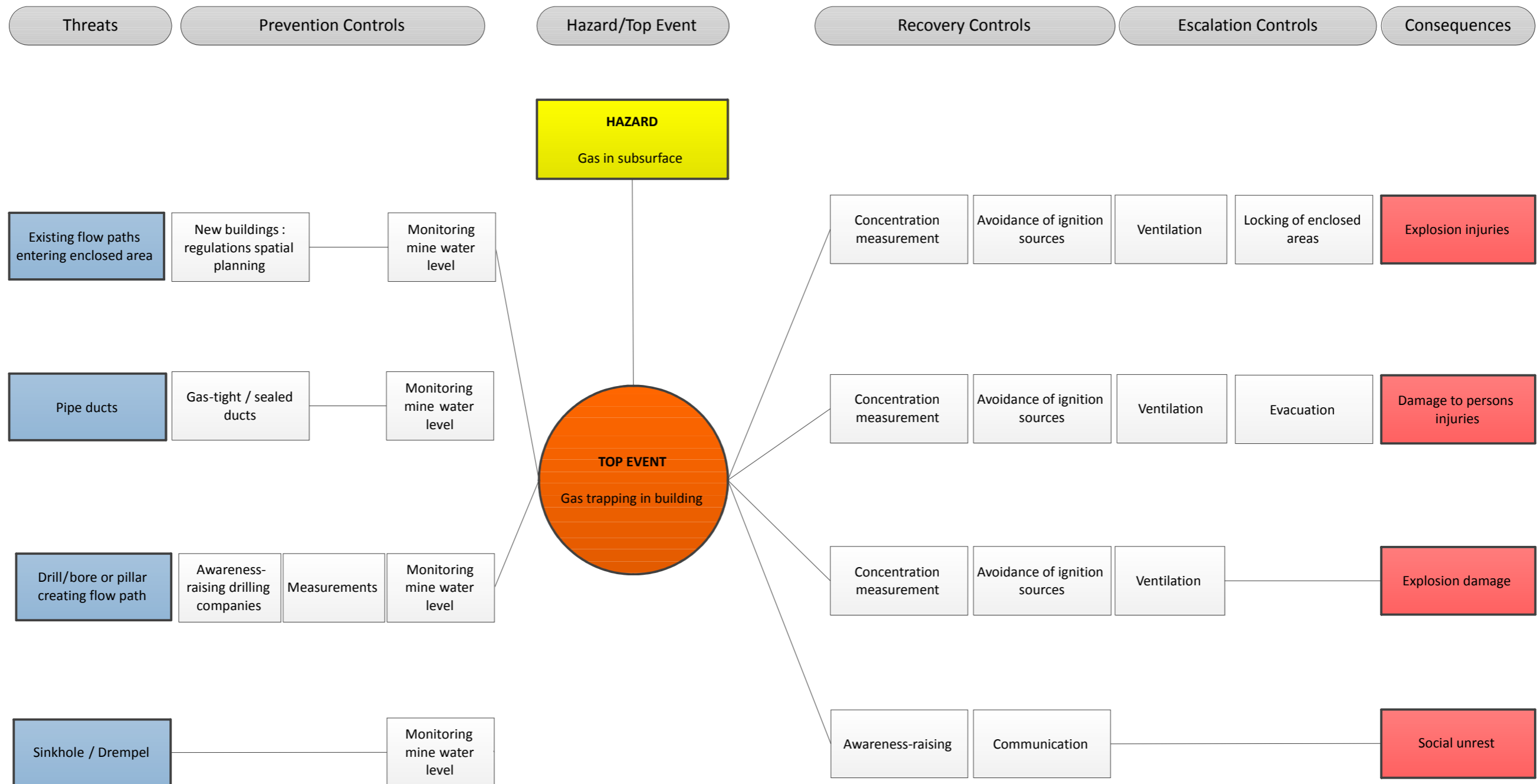
5.2.4 Groundwater quality



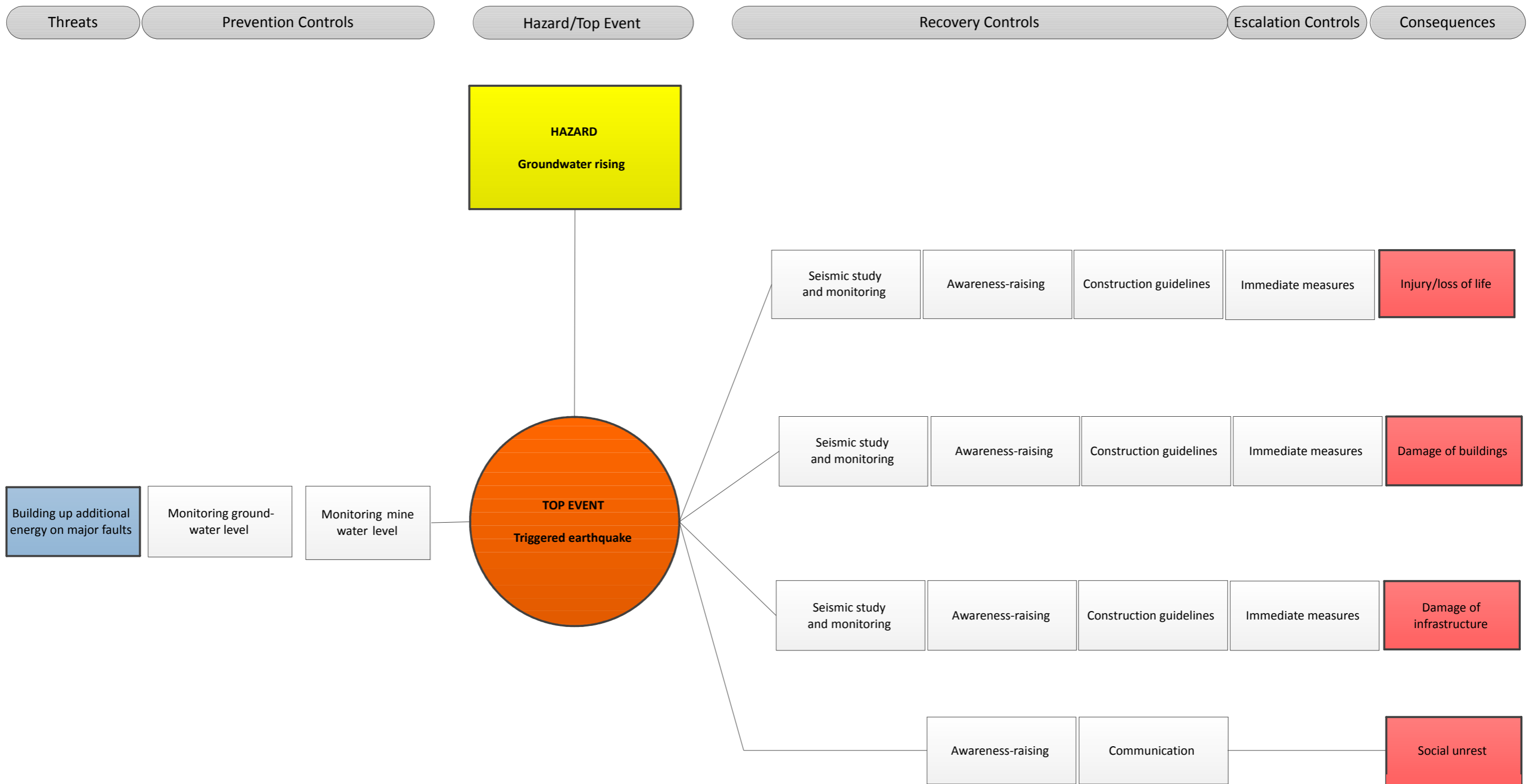
5.2.5 Groundwater quantity



5.2.6 Mine gas



5.2.7 Small earthquakes



Appendix 2

**Na-ijlende gevolgen steenkolenwinning
Zuid-Limburg**

Summary report
with integrated Bow-Tie-Analysis

Integrated Bow-Tie-Analysis
for ranking of preventive controls - decision matrix

by

Projectgroup
"Na-ijlende gevolgen van de steenkolenwinning in
Zuid-Limburg"
(projectgroup GS-ZL)

on behalf of
Ministerie van Economische Zaken - The Netherlands

Aachen (D) / Deventer (NL), 30.09.2016

Usefulness of prevention controls

Group 1 (18 to 12 points)	Number of appearance	Total score	Average score	Lowest score	Highest Score	Useful for working group
Remediation measures at 6 industrial shafts	6	108	18,0	18	18	5.2.2 (i)
Remediation measures	5	90	18,0	18	18	5.2.2 (h)
Limitation of seepage water influx	11	90	8,2	6	12	5.2.2 (h) / 5.2.2 (i)
Monitoring mine water level	13	63,2	4,9	0,4	12	5.2.1 / 5.2.4 / 5.2.5 / 5.2.6 / 5.2.7
Safeguarding	5	60	12,0	12	12	5.2.2 (h)
Limitation of loads in the vicinity of shaft head	6	54	9,0	6	12	5.2.2 (h) / 5.2.2 (i)
Monitoring groundwater level	9	47,8	5,3	0,6	12	5.2.1 / 5.2.4 / 5.2.5 / 5.2.7
Stabilisation of underground mine voids and rock roof	3	36	12,0	12	12	5.2.3
Monitoring groundwater quality	3	36	12,0	12	12	5.2.4
Limitation of loads on shaft head	3	30	10,0	6	12	5.2.2 (h) / 5.2.2 (i)

Group 2 (11 to 6 points)

Monitoring industrial shafts	6	36	6,0	6	6	5.2.2 (i)
Site inspections (historical shafts)	5	30	6,0	6	6	5.2.2 (h)
Monitoring ground heave	3	18	6,0	6	6	5.2.1
New buildings: regulations spatial planning	1	6	6,0	6	6	5.2.6
Gas-tight / sealed ducts	1	6	6,0	6	6	5.2.6
Awareness-raising drilling companies	1	6	6,0	6	6	5.2.6
Measurements (mine gas)	1	6	6,0	6	6	5.2.6

Group 3 (5 to 0 points)

Regulation of groundwater extraction in potential impact area Ia/b	3	12	4,0	4	4	5.2.4
Change configuration wells in potential impact area Ia/b	1	4	4,0	4	4	5.2.4
Research hydr. connections in the potential impact areas	1	4	4,0	4	4	5.2.4
Develop early warning system	3	1,2	0,4	0,4	0,4	5.2.5
Restrictions catchment area	1	0,2	0,2	0,2	0,2	5.2.5
Geohydrological research	1	0,2	0,2	0,2	0,2	5.2.5

Usefulness of "preventive recovery controls"

		Usefulness	Cost	Effectiveness
Group 4 ("preventive recovery controls")	Useful for working group	Group	Group	Category
Awareness-raising	general	1	1	0
Communication	general	1	1	0
Detailed monitoring three potential impact areas differential ground heave	5.2.1	1	2	1
Pilot research Geleen	5.2.1	already assigned		
Inventory sensitive structures in the three potential areas	5.2.1	2	2	3
Regional development planning	5.2.1 / 5.2.2 / 5.2.3 / 5.2.4	1	1	0
Adapted site investigation	5.2.2 / 5.2.3	1	1	0
Adapted construction / construction guidelines	5.2.1 / 5.2.2 / 5.2.3 / 5.2.5	1	1	0
Pilot research Heerlen	5.2.3	already assigned		
Development early warning system (ground movements)	5.2.3	3	2	3
Development early warning system (water motion)	5.2.4	3	3	3
Seismic study and monitoring	5.2.7	3	3	3

Cost estimation in
App. 3

Costs roughly
approximated

Cost group	Investment [€] excl. VAT	Operational costs for 5 years [€] excl. VAT
1	≤ 80.000	≤ 10.000
2	> 80.000 - 1.200.000	> 10.000 - 150.000
3	> 1.200.000 - 8.000.000	> 150.000 - 1.000.000
4	> 8.000.000 - 20.000.000	> 1.000.000 - 2.500.000
5	> 20.000.000	> 2.500.000

Effectiveness of prevention controls

			Score	Useful for working group	Costs				Effectiveness	
					Investment	Operational costs for 5 years	Total	Group		
					[€] excl. VAT	[€] excl. VAT	[€] excl. VAT			
Group 1 (18 to 12 points)										
Remediation measures at 6 industrial shafts			18	5.2.2 (i)	1.100.000	0	1.100.000	2	1	
Remediation measures			18	5.2.2 (h)	10.950.000	0	10.950.000	4	2	
Safeguarding historical shafts			12	5.2.2 (h)					0	
Limitation of seepage water influx at shafts			12	5.2.2 (h) / 5.2.2 (i)						
Limitation of loads in the vicinity of shaft heads			12	5.2.2 (h) / 5.2.2 (i)						
Limitation of loads on shaft heads			12	5.2.2 (h) / 5.2.2 (i)						
Stabilisation of underground mine voids and rock roof			12	5.2.3	37.179.000	0	37.179.000	5		
Monitoring mine water level			12	5.2.1 / 5.2.4 / 5.2.5 / 5.2.6 / 5.2.7				2		
Monitoring groundwater level			12	5.2.1 / 5.2.4 / 5.2.5 / 5.2.7	670.150	20.200	690.350	2	1	
Monitoring groundwater quality			12	5.2.4		78.144	78.144	2	1	
Group 2 (11 to 6 points)										
Monitoring industrial mine shafts			6	5.2.2 (i)	300.000	54.000	354.000	2	1	
Site inspections (historical shafts)			6	5.2.2 (h)	0	100.000	100.000	2	1	
Monitoring ground heave	InSAR: regional overview		6	5.2.1 (three alternatives with increasing precision according to actual needs)	9.000	252.500	261.500	3	2	
	InSAR: detail potential impact zones				9.000	772.500	781.500	3	3	
	InSAR: high detail potential impact zones / new GNSS stations / Levelling				222.000	1.400.000	1.622.000	4	4	
New buildings: regulations spatial planning regarding mine gas			6	5.2.6			AT	1	0	
Gas-tight / sealed ducts			6	5.2.6			AT	1	0	
Awareness-raising drilling companies regarding mine gas			6	5.2.6			AT	1	0	
Measurements (mine gas)			6	5.2.6	103.000	170.000	273.000	3	1	
Group 3 (5 to 0 points)										
Regulation of groundwater extraction in potential impact area Ia/b			4	5.2.4	-	-	-	-	4	ExO
Change configuration wells in potential impact area Ia/b			4	5.2.4	-	-	-	-	4	ExO
Research hydr. connections in the potential impact areas			4	5.2.4	-	-	-	-	3	ExO
Develop early warning system			0,4	5.2.5	-	-	-	-	3	ExO
Restrictions catchment area			0,2	5.2.5			AT	-	3	ExO
Geohydrological research			0,2	5.2.5	-	-	-	-	3	ExO

Administrative task AT

ExO - expert opinion

(h) - historical shafts
(i) - industrial shafts

≤ 80.000	≤ 10.000		Group 1
> 80.000 - 1.200.000	> 10.000 - 150.000		Group 2
> 1.200.000 - 8.000.000	> 150.000 - 1.000.000		Group 3
> 8.000.000 - 20.000.000	> 1.000.000 - 2.500.000		Group 4
> 20.000.000	> 2.500.000		Group 5

Cat. 0	No regret	
Cat. 1	Strongly recommended	Need action
Cat. 2	Recommended	Additional actions
Cat. 3	Good to have	Reconsider
Cat. 4	Not advisable for the time being	Skip or carry out later, if a new situation requires additional action
Cat. 5	Inadequate for the time being	

Appendix 3

**Na-ijlende gevolgen steenkolenwinning
Zuid-Limburg**

Summary report
with integrated Bow-Tie-Analysis

Cost indication for measures and monitoring

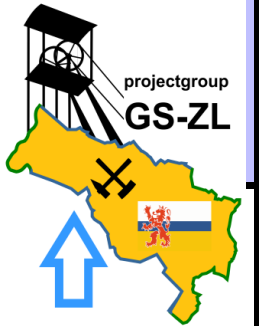
by

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on behalf of
Ministerie van Economische Zaken - The Netherlands

Aachen (D) / Deventer (NL), 30.09.2016

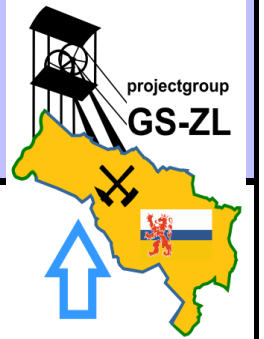
Cost indication Measures all working groups



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)
Working group 5.2.1 Ground movements		
First-order priority - InSAR: regional overview, local detailed levelling	9.000	336.500
Second-order priority - in addition InSAR: regional detail	0	520.000 (additional costs)
Third-order priority - in addition InSAR: regional high detail/regional levelling/new GNSS stations	213.000 (additional costs)	627.500 (additional costs)
Working group 5.2.2 Mine shafts		
Historical mine shafts		
- Search, investigation 59 shafts (total investment 2.950.000 eur)	2.950.000	
- Remediation 40 historical shafts (4 shafts/year, total investment 8.000.000 eur)	8.000.000	
- Site inspection		100.000
Industrial mine shafts		
- Remediation 6 shafts	1.100.000	
- Installation monitoring	300.000	
- Monitoring		54.000
Working group 5.2.3 Near-surface mining		
Near-surface mining		
- 9.000 m outcrop lines impact category EK 1 and EK 2 project area 1	27.000.000	
- 26 patches with impact category EK 1 and EK 2 in project area 2 and 3	9.802.000	
- Pilot project 4	377.000	
Working group 5.2.4/5.2.5 Groundwater quality and quantity		
Monitoring groundwater quality (1/year, 6 wells, 4 filters/well)		78.144
Monitoring groundwater quantity (high frequency, 7 wells, 26 Divers total)	133.900	20.200
Piezometers (drilling, engineering, supervision)	436.250	
Legal arrangements	100.000	
Working group 5.2.6 Mine gas		
Existing buildings (30 buildings)	53.000	70.000
New buildings (10 buildings)		50.000
New buildings		
- Gas warning device	50.000	50.000
Working group 5.2.7 Small earthquakes		
- Seismic study/seismic line	500.000	
Total (all measurements)	50.811.150	758.844
Total (recommended = all measures green and yellow, excluded measures near-surface mining)	13.456.150	638.844

Cost indication Measures WG 5.2.1



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)

Working group 5.2.1 Ground movements

First-order priority

GNSS existing stations	0	50.000
3 Transponders	9.000	7.500
Medium-resolution InSAR (asc+dsc)	0	180.000
Yearly inspection levelling benchmarks	0	15.000
Detailed local levelling (recovery control)	0	(84.000)
Total First-order priority prevention controls	9.000	252.500

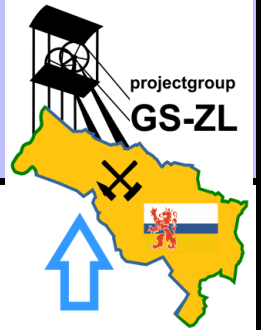
Second-order priority

High-resolution InSAR (asc or dsc)	0	700.000
Cost additional to First-order priority	0	520.000
Total Second-order priority prevention controls	9.000	772.500

Third-order priority

GNSS 6 new stations	174.000	75.000
13 additional transponders	39.000	32.500
High-resolution InSAR (asc and dsc, additional costs)	0	400.000
Regional levelling	0	120.000
Cost additional to Second-order priority	213.000	627.500
Total Third-order priority prevention controls	222.000	1.400.000

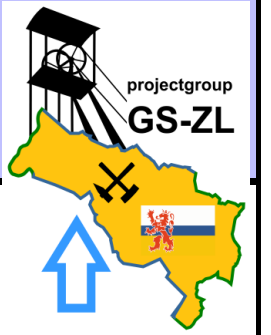
Cost indication Measures WG 5.2.2



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)
Working group 5.2.2 Mine shafts		
Historical mine shafts		
- Search, investigation 59 shafts (50.000 eur/shaft)	2.950.000	
- Remediation 40 historical shafts (200.000 eur/shaft)	8.000.000	
- Site inspections		100.000
Remediation industrial mine shafts		
- Buizenschacht (Domaniale)	190.000	
- Willem I (Domaniale)	190.000	
- Willem II (Domaniale)	190.000	
- Beerenbosch I (Domaniale)	170.000	
- Neuland (Domaniale)	220.000	
- Melanie (Willem Sophia)	140.000	
Installation monitoring (30 shafts)	300.000	
Annual monitoring of 4 shafts		2.000
Quarterly monitoring of 26 shafts		52.000
Total	12.350.000	154.000

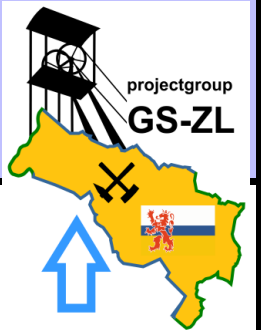
Cost indication Measures WG 5.2.3



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)
Working group 5.2.3 Near-surface mining		
Project area 1		
- 9.000 m of outcrop lines of impact category EK1 and EK 2 (3.000 eur/m)	27.000.000	
Project area 2 and 3		
- 26 patches with impact category EK1 and EK 2 (377.000 eur/patch)	9.802.000	
- Pilot project 4 investigation	87.000	
- Pilot project 4 remediation	290.000	
Total	37.179.000	0

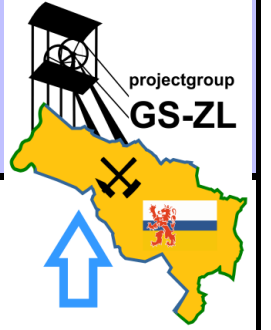
Cost indication Measures WG 5.2.4 and WG 5.2.5



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)
Working group 5.2.4/5.2.5 Groundwater quality and quantity		
Monitoring groundwater quality (1/year, 6 wells, 4 filters/well)		
- Macrochemistry (170 eur/sample)		20.400
- Heavy metals (46 eur/sample)		5.520
- Pollution (160 eur/sample)		19.200
- 20% margin		9.024
- Sample taking		24.000
High frequency EC, Temp and heads (daily with CTD-Divers)		
Monitoring groundwater quantity (high frequency, 7 wells, 26 Divers total)		
- CTD-Divers (5 wells, 20 Divers)	39.000	
- Cables and modem	36.400	
- Admission domain	26.000	
- Installation and maintainance	32.500	5.200
- Reports (3.000 eur/year)		15.000
Piezometers (drilling, engineering, supervision)		
- I (next to well B60C0860): 300 metres depth	105.000	
- II (eastern boundary Maurits concession): 300 metres depth	105.000	
- III (next to well B60C0839): 195 metres depth	68.250	
- IV (near well B62B0838): 140 metres depth	49.000	
- V (near well B62B0837): 140 metres depth	49.000	
- VI ('t Loon Heerlen): 60 metres depth	18.000	
- VII (north Heerlerheide fault): 140 metres depth	42.000	
Legal arrangements	100.000	
Total	670.150	98.344

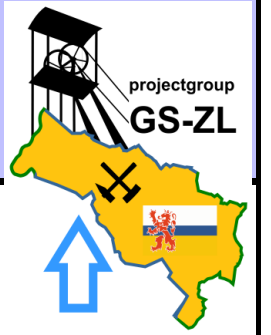
Cost indication Measures WG 5.2.6



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)
Working group 5.2.6 Mine gas		
Existing buildings		
- Investigation buildings in type C area	40.000	
- Measurement current state (30 buildings)	13.000	
- Ongoing monitoring (2 times/year)		70.000
New buildings (10 buildings)		50.000
- Construction guidelines		
- Gas warning systems		
New buildings		
- Gas warning device	50.000	
- Calibration devices		50.000
Total	103.000	170.000

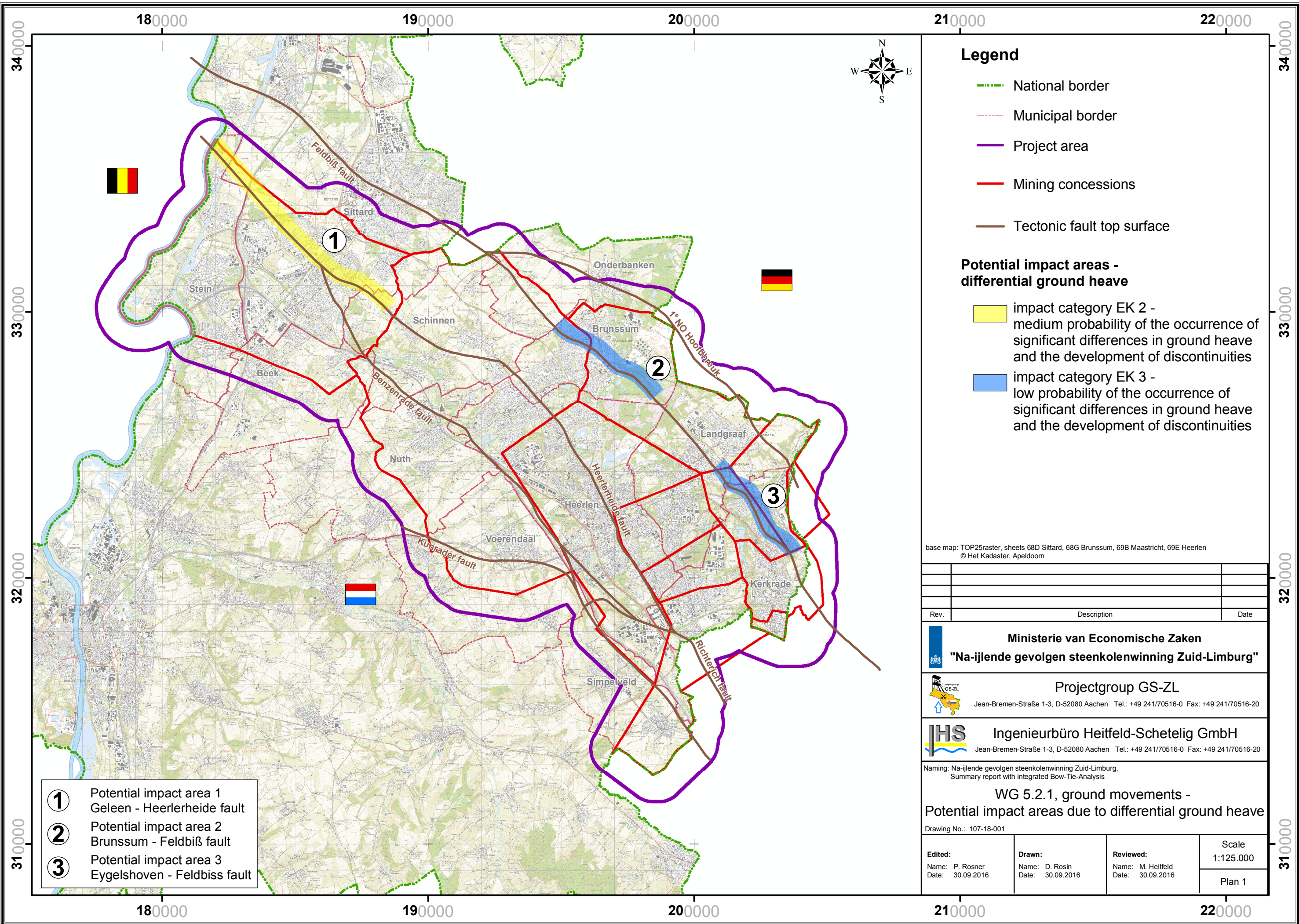
Cost indication Measures WG 5.2.7



Project Na-ijlende gevolgen steenkolenwinning Zuid-Limburg
Client Ministerie EZ/IHS
Code
Revision 001

	Investment (installation, engineering, fieldwork, remediation) € (excl VAT)	Operational costs (5 year) € (excl VAT)
Working group 5.2.7 Small earthquakes		
- Seismic study/seismic line	500.000	
Total	500.000	0

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Legend

- National border
- Municipal border
- Project area
- Mining concessions
- Tectonic fault top surface

Potential impact areas - differential ground heave

- impact category EK 2 - medium probability of the occurrence of significant differences in ground heave and the development of discontinuities
- impact category EK 3 - low probability of the occurrence of significant differences in ground heave and the development of discontinuities

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen © Het Kadaster, Apeldoorn

Rev.	Description	Date

Ministerie van Economische Zaken
"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

Projectgroep GS-ZL
 Jean-Bremen-Straße 1-3, D-52080 Aachen Tel.: +49 241/70516-0 Fax: +49 241/70516-20

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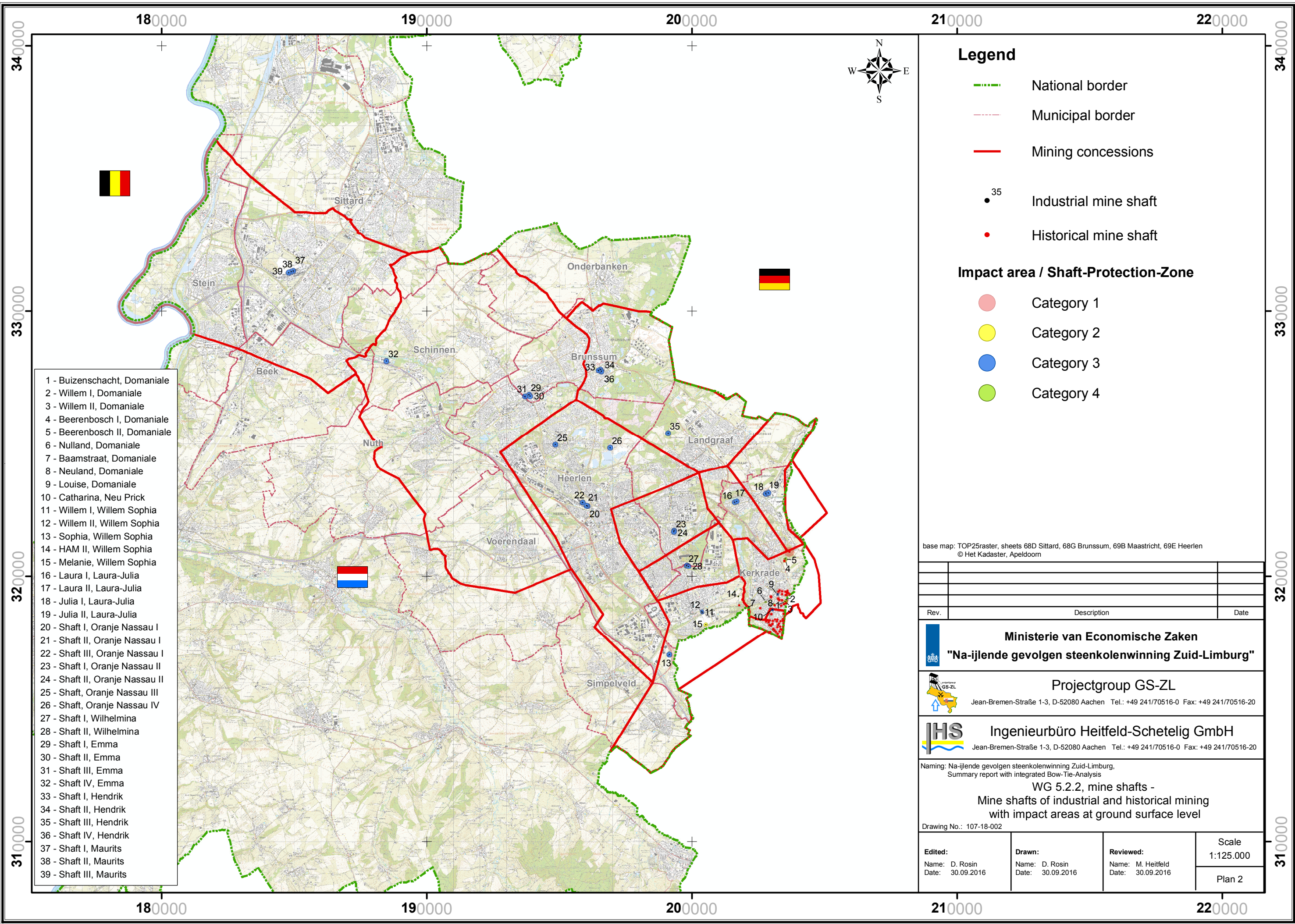
Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg, Summary report with integrated Bow-Tie-Analysis

WG 5.2.1, ground movements - Potential impact areas due to differential ground heave






Drawing No.: 107-18-001

Edited: Name: P. Rosner Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000 Plan 1
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- 1** Potential impact area 1
Geleen - Heerlerheide fault
- 2** Potential impact area 2
Brunssum - Feldbiß fault
- 3** Potential impact area 3
Eyselshoven - Feldbiss fault



Legend

-  National border
-  Municipal border
-  Mining concessions
-  35 Industrial mine shaft
-  Historical mine shaft

Impact area / Shaft-Protection-Zone

-  Category 1
-  Category 2
-  Category 3
-  Category 4

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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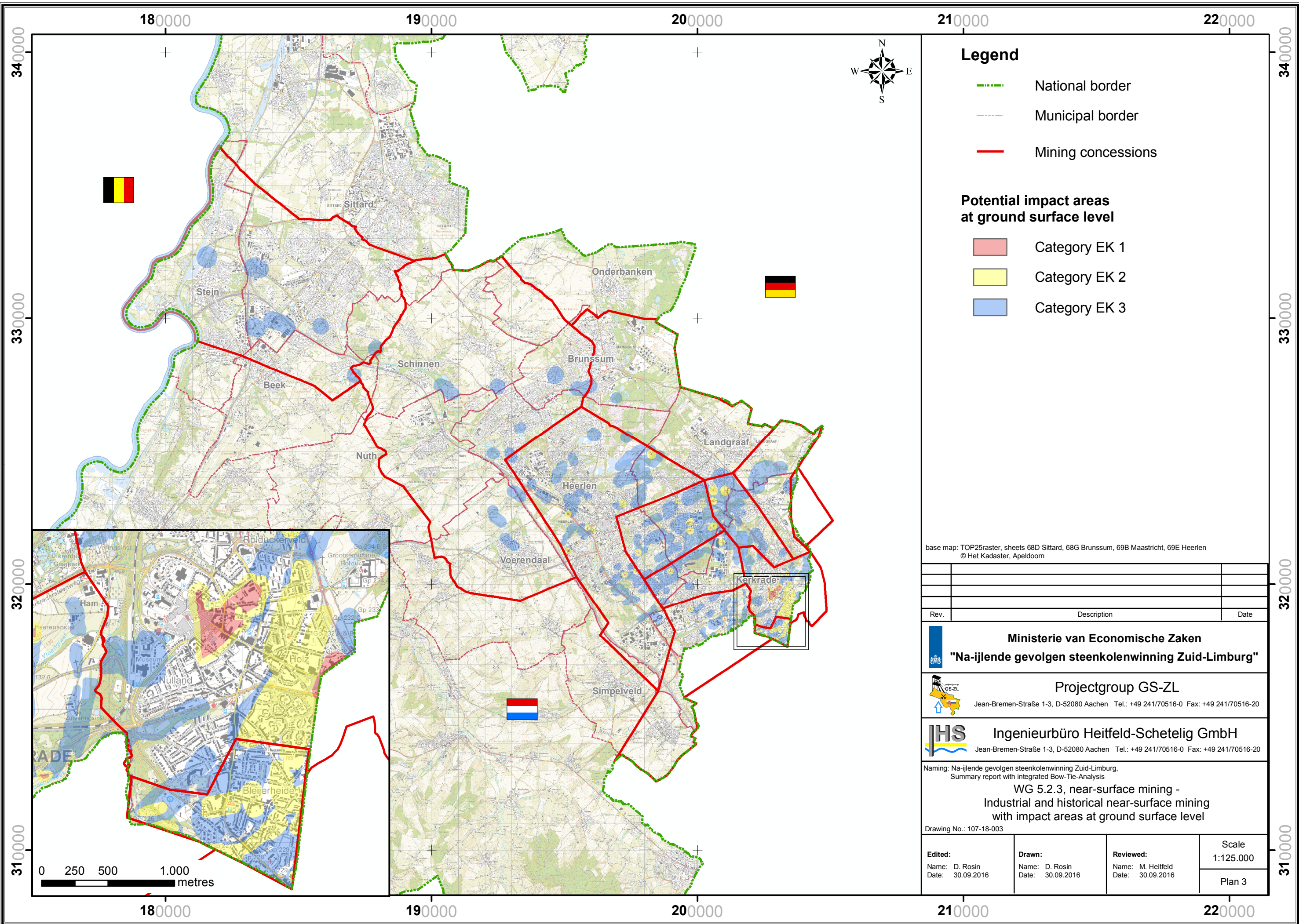
IHS Ingenieurbüro Heitfeld-Schetelig GmbH
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
Summary report with integrated Bow-Tie-Analysis
WG 5.2.2, mine shafts -
Mine shafts of industrial and historical mining
with impact areas at ground surface level




Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000 Plan 2
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- 1 - Buizenschacht, Domaniale
- 2 - Willem I, Domaniale
- 3 - Willem II, Domaniale
- 4 - Beerenbosch I, Domaniale
- 5 - Beerenbosch II, Domaniale
- 6 - Nulland, Domaniale
- 7 - Baamstraat, Domaniale
- 8 - Neuland, Domaniale
- 9 - Louise, Domaniale
- 10 - Catharina, Neu Prick
- 11 - Willem I, Willem Sophia
- 12 - Willem II, Willem Sophia
- 13 - Sophia, Willem Sophia
- 14 - HAM II, Willem Sophia
- 15 - Melanie, Willem Sophia
- 16 - Laura I, Laura-Julia
- 17 - Laura II, Laura-Julia
- 18 - Julia I, Laura-Julia
- 19 - Julia II, Laura-Julia
- 20 - Shaft I, Oranje Nassau I
- 21 - Shaft II, Oranje Nassau I
- 22 - Shaft III, Oranje Nassau I
- 23 - Shaft I, Oranje Nassau II
- 24 - Shaft II, Oranje Nassau II
- 25 - Shaft, Oranje Nassau III
- 26 - Shaft, Oranje Nassau IV
- 27 - Shaft I, Wilhelmina
- 28 - Shaft II, Wilhelmina
- 29 - Shaft I, Emma
- 30 - Shaft II, Emma
- 31 - Shaft III, Emma
- 32 - Shaft IV, Emma
- 33 - Shaft I, Hendrik
- 34 - Shaft II, Hendrik
- 35 - Shaft III, Hendrik
- 36 - Shaft IV, Hendrik
- 37 - Shaft I, Maurits
- 38 - Shaft II, Maurits
- 39 - Shaft III, Maurits

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Legend

-  National border
-  Municipal border
-  Mining concessions

Potential impact areas at ground surface level

-  Category EK 1
-  Category EK 2
-  Category EK 3

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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Rev.	Description	Date

Ministerie van Economische Zaken
"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

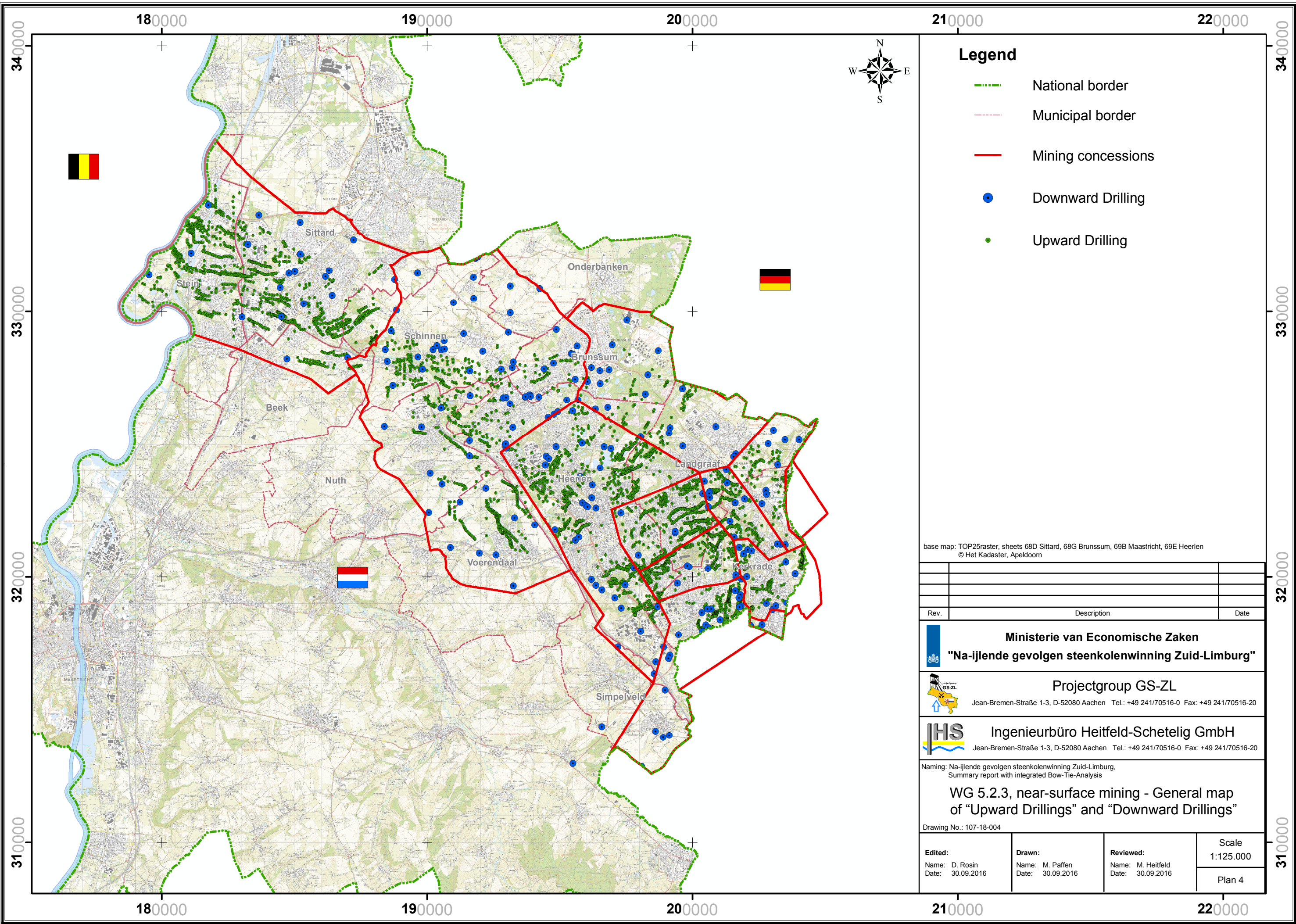
Projectgroup GS-ZL
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IHS Ingenieurbüro Heitfeld-Schetelig GmbH
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
Summary report with integrated Bow-Tie-Analysis
**WG 5.2.3, near-surface mining -
Industrial and historical near-surface mining
with impact areas at ground surface level**

Drawing No.: 107-18-003

Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000 Plan 3
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- Legend**
- - - - National border
 - - - - Municipal border
 - Mining concessions
 - Downward Drilling
 - Upward Drilling



base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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Rev.	Description	Date

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"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

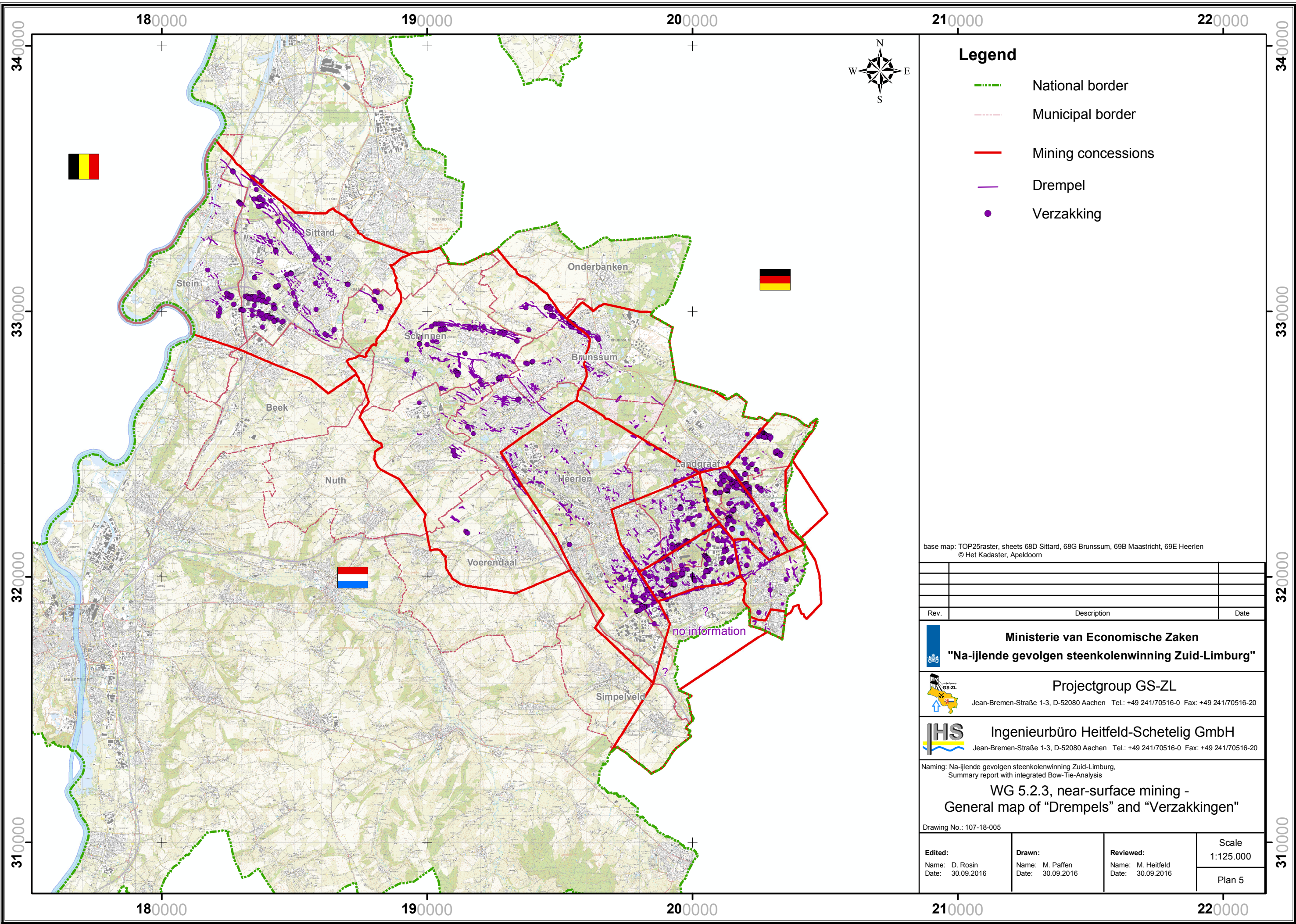
Projectgroup GS-ZL
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
Summary report with integrated Bow-Tie-Analysis
**WG 5.2.3, near-surface mining - General map
of "Upward Drillings" and "Downward Drillings"**
Drawing No.: 107-18-004

Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: M. Paffen Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000 Plan 4
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- Legend**
- - - National border
 - - - Municipal border
 - Mining concessions
 - Drempel
 - Verzakking

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

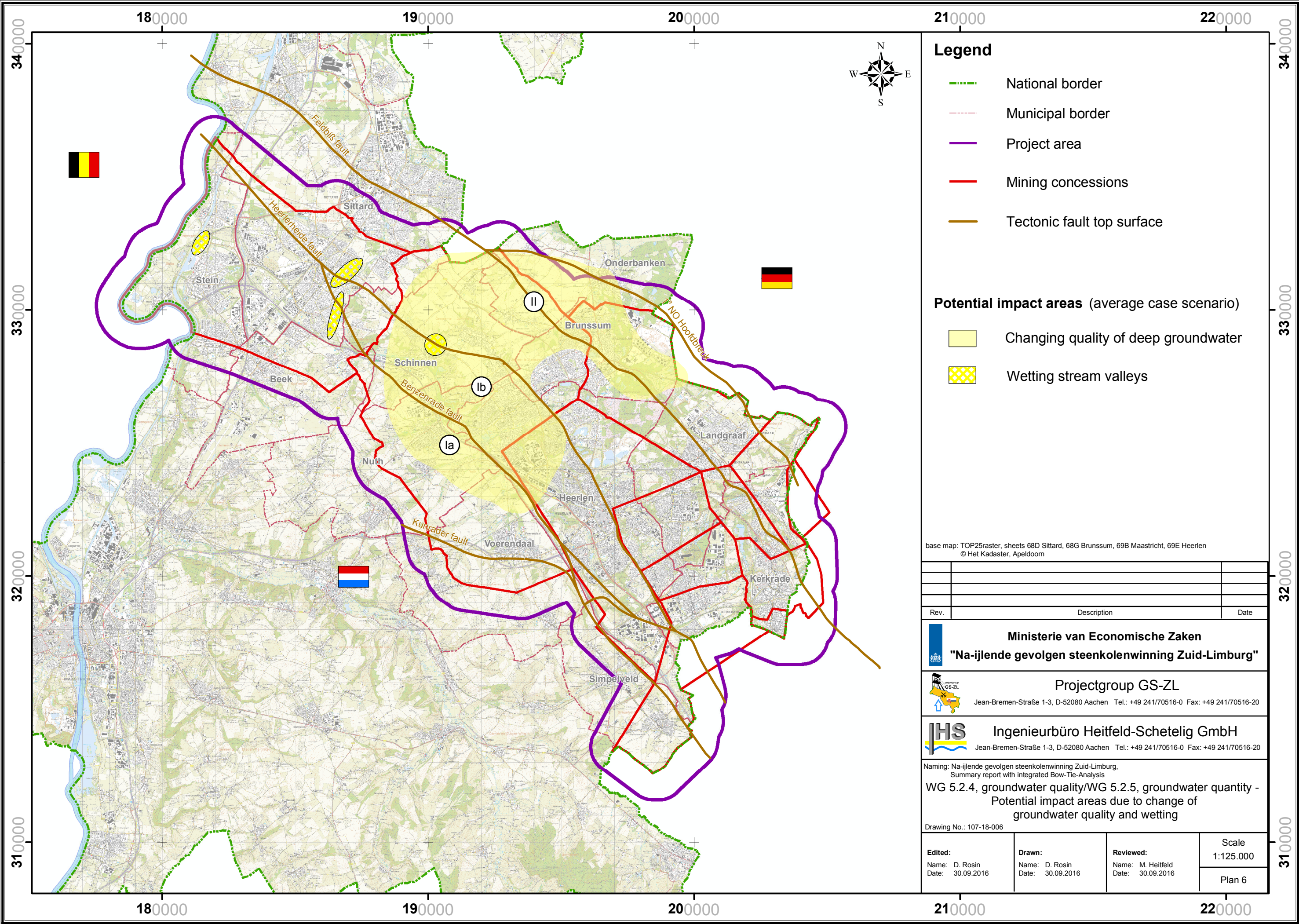
Projectgroup GS-ZL
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
Summary report with integrated Bow-Tie-Analysis
**WG 5.2.3, near-surface mining -
General map of "Drempels" and "Verzakkingen"**

Drawing No.: 107-18-005		Scale 1:125.000	
Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: M. Paffen Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Plan 5

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Legend

- National border
- Municipal border
- Project area
- Mining concessions
- Tectonic fault top surface

Potential impact areas (average case scenario)

- Changing quality of deep groundwater
- Wetting stream valleys

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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Rev.	Description	Date

Ministerie van Economische Zaken
"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

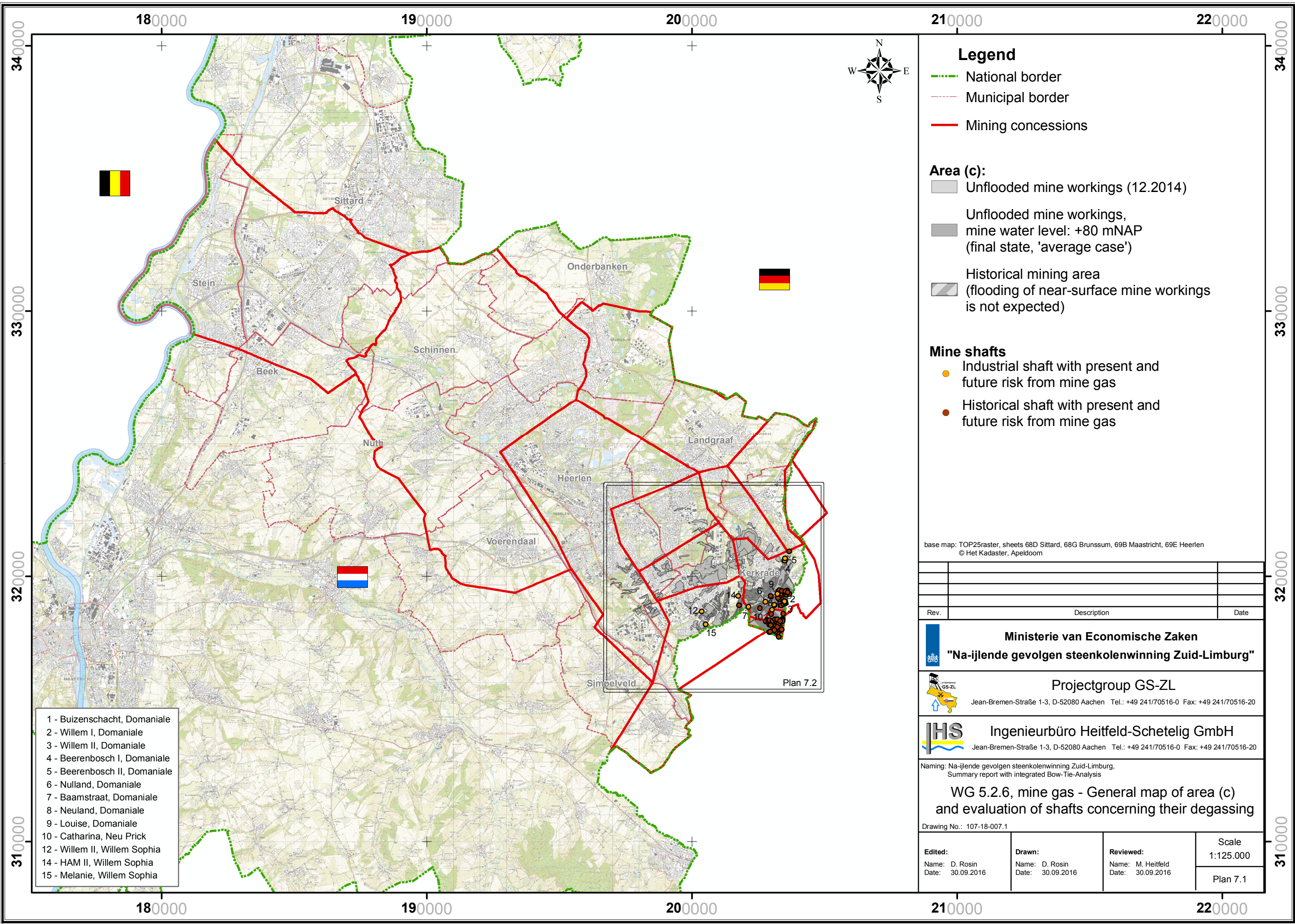
Projectgroup GS-ZL
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
 Summary report with integrated Bow-Tie-Analysis
WG 5.2.4, groundwater quality/WG 5.2.5, groundwater quantity -
Potential impact areas due to change of
groundwater quality and wetting

Drawing No.: 107-18-006

Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000 Plan 6
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- 1 - Buizenschacht, Domaniale
- 2 - Willem I, Domaniale
- 3 - Willem II, Domaniale
- 4 - Beerenbosch I, Domaniale
- 5 - Beerenbosch II, Domaniale
- 6 - Nulland, Domaniale
- 7 - Baamstraat, Domaniale
- 8 - Neuland, Domaniale
- 9 - Louise, Domaniale
- 10 - Catharina, Neu Prick
- 12 - Willem II, Willem Sophia
- 14 - HAM II, Willem Sophia
- 15 - Melanie, Willem Sophia

Legend

- - - National border
- - - Municipal border
- Mining concessions

Area (c):

- Unflooded mine workings (12.2014)
- Unflooded mine workings, mine water level: +80 mNAP (final state, 'average case')
- Historical mining area (flooding of near-surface mine workings is not expected)

Mine shafts

- Industrial shaft with present and future risk from mine gas
- Historical shaft with present and future risk from mine gas

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

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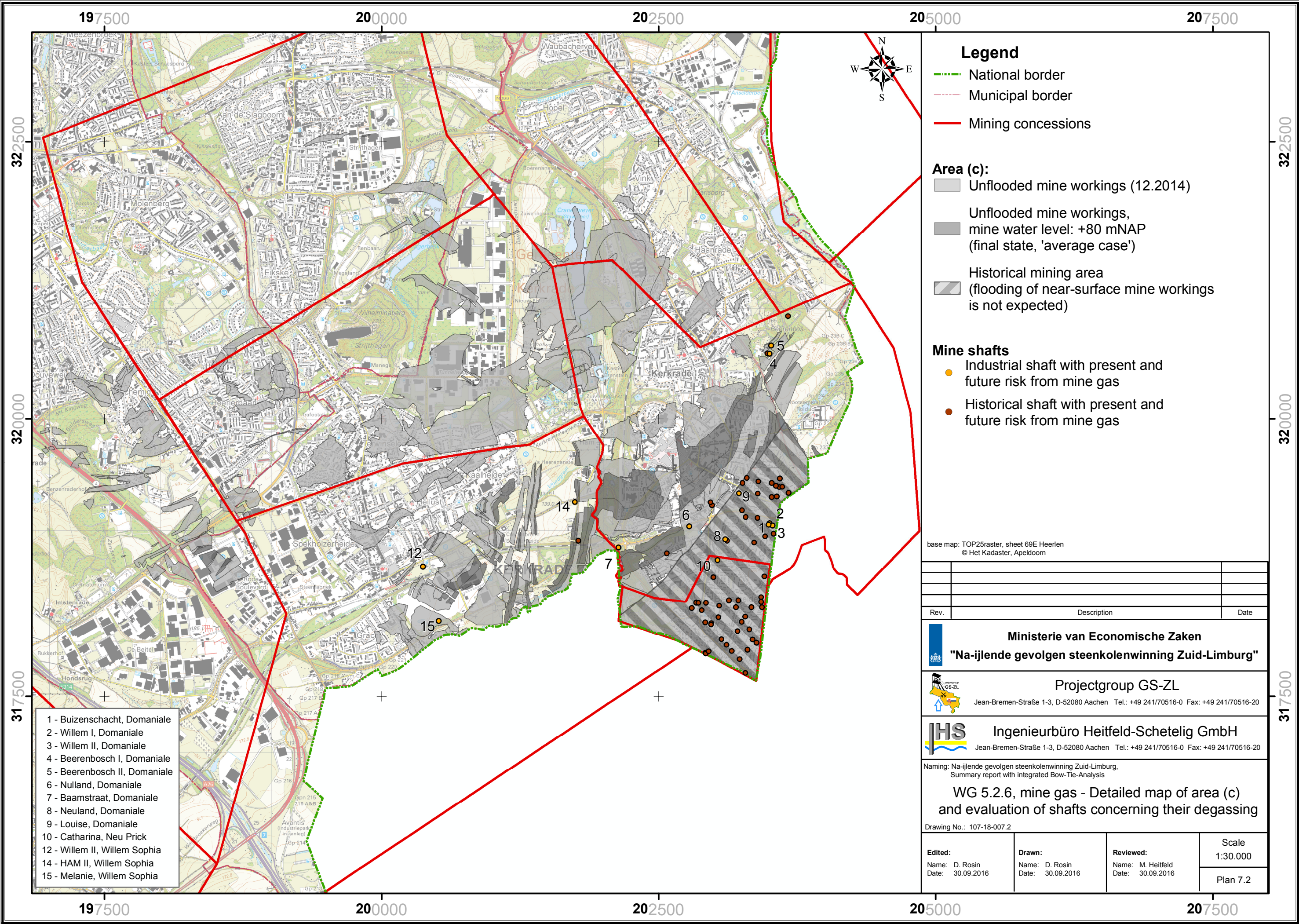
Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
Summary report with integrated Bow-Tie-Analysis

**WG 5.2.6, mine gas - General map of area (c)
and evaluation of shafts concerning their degassing**

Drawing No.: 107-18-007.1

Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000 Plan 7.1
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- Legend**
- National border
 - Municipal border
 - Mining concessions
- Area (c):**
- Unflooded mine workings (12.2014)
 - Unflooded mine workings, mine water level: +80 mNAP (final state, 'average case')
 - Historical mining area (flooding of near-surface mine workings is not expected)
- Mine shafts**
- Industrial shaft with present and future risk from mine gas
 - Historical shaft with present and future risk from mine gas

base map: TOP25raster, sheet 69E Heerlen
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Rev.	Description	Date

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Projectgroep GS-ZL
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg, Summary report with integrated Bow-Tie-Analysis

WG 5.2.6, mine gas - Detailed map of area (c) and evaluation of shafts concerning their degassing

Drawing No.: 107-18-007.2

Edited: Name: D. Rosin Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:30.000 Plan 7.2
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- 1 - Buizenschacht, Domaniale
- 2 - Willem I, Domaniale
- 3 - Willem II, Domaniale
- 4 - Beerenbosch I, Domaniale
- 5 - Beerenbosch II, Domaniale
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- 14 - HAM II, Willem Sophia
- 15 - Melanie, Willem Sophia

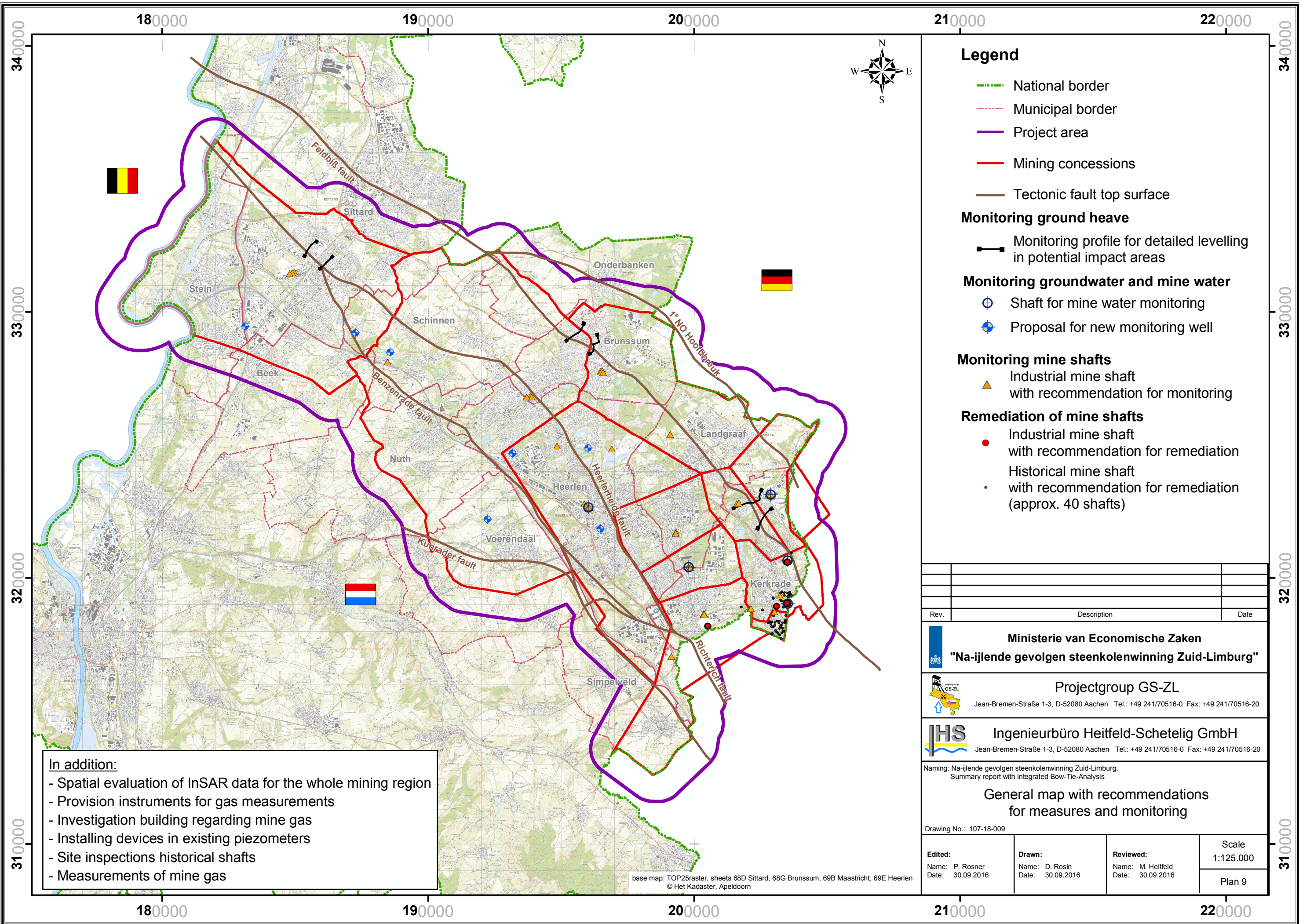
Plan for monitoring and measures

		Year				
Monitoring	Measures	1	2	3	4	5
Cat. 0 - no regret						
	New buildings: regulations spatial planning regarding mine gas					
	Gas-tight / sealed ducts					
	Awareness-raising drilling companies regarding mine gas					
Temporal measures						
	Limitation of seepage water influx at mine shafts					
	Limitation of loads on shaft heads and in the vicinity					
Additional: Selected „preventive recovery controls“						
	Awareness-raising					
	Communication					
	Regional development planning					
	Adapted site investigation					
	Adapted construction / Construction guidelines					
Cat. 1 - Strongly recommended						
	Remediation measures at 6 industrial mine shafts					
	Installation monitoring equipment at industrial mine shafts					
	Provision instruments for gas measurements					
	Investigation building regarding mine gas					
	Installing new piezometers					
	Installing measurement devices in existing piezometers					
	Installing levelling benchmarks for the detailed profile in three potential impact areas					
	Monitoring mine water level					
	Monitoring groundwater level					
	Monitoring groundwater quality					
	Monitoring industrial mine shafts					
	Site inspections (historical mine shafts)					
	Detailed monitoring three potential impact areas differential ground heave (levelling)					
	Measurements (mine gas)					
Cat. 2 - Recommended						
	Remediation measures historical mine shafts					
	Monitoring ground heave: InSAR: Regional overview					

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Rev.	Description	Date
 Ministerie van Economische Zaken "Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"		
 Projectgroep GS-ZL Jean-Bremen-Straße 1-3, D-52080 Aachen Tel.: +49 241/70516-0 Fax: +49 241/70516-20		
 Ingenieurbüro Heitfeld - Schetelig GmbH Jean-Bremen-Straße 1-3, 52080 Aachen Tel.: 0241/70516-0 Fax: 0241/70516-20		
Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg. Summary report with integrated Bow-Tie-Analysis		
Monitoring and Measure plan		
Drawing No.: 107-18-008		
Edited: Name: P. Rosner Date: 30.09.2016	Drawn: Name: J. Boger Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016
		Plan 8

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Legend

- National border
- Municipal border
- Project area
- Mining concessions
- Tectonic fault top surface
- Monitoring ground heave**
 - Monitoring profile for detailed levelling in potential impact areas
- Monitoring groundwater and mine water**
 - Shaft for mine water monitoring
 - Proposal for new monitoring well
- Monitoring mine shafts**
 - Industrial mine shaft with recommendation for monitoring
- Remediation of mine shafts**
 - Industrial mine shaft with recommendation for remediation
 - Historical mine shaft with recommendation for remediation (approx. 40 shafts)

Rev.	Description	Date

Ministerie van Economische Zaken
"Na-ijlende gevolgen steenkolenwinning Zuid-Limburg"

Projectgroup GS-ZL
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Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg, Summary report with integrated Bow-Tie-Analysis

General map with recommendations for measures and monitoring

Drawing No.: 107-18-009

Edited: Name: P. Rosner Date: 30.09.2016	Drawn: Name: D. Rosin Date: 30.09.2016	Reviewed: Name: M. Heitfeld Date: 30.09.2016	Scale 1:125.000
			Plan 9

In addition:

- Spatial evaluation of InSAR data for the whole mining region
- Provision instruments for gas measurements
- Investigation building regarding mine gas
- Installing devices in existing piezometers
- Site inspections historical shafts
- Measurements of mine gas

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen © Het Kadaster, Apeldoorn