Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working groups
5.2.4 - groundwater quality
5.2.5 - groundwater quantity

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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WG 5.2.4 - groundwater quality and WG 5.2.5 - groundwater quantity -
Final report

This report is edited by

Ingenieursbureau Witteveen+Bos
Van Twickelostraat 2
7400 AE Deventer
The Netherlands
Telephone: +31 (570) 697911
E-mail: info@witteveenbos.com

Authors:
ir. Jaap H. Spaans
Dipl.-Geol. Nancy Sevriens-Visser
Drs. Arie Biesheuvel

Ingenieurbüro ahu AG
Kirberichshofer Weg 6
52066 Aachen
Germany
Telephone: +49 (241) 900011-0
E-mail: info@ahu.de

Author:
Dr. Michael Denneborg

Ingenieurbüro Heitfeld Schetelig GmbH
Jean-Bremen-Straße 1-3
52080 Aachen
Germany
Telephone: +49 (241) 70516 -0
E-mail: info@ihs-online.de

Authors:
Dr.-Ing. Michael Heitfeld
Dr. Peter Rosner

with contributions by
Van Rooijen Adviezen
Grubenweg 20A
6343 CC Klimmen
The Netherlands
Telephone: +31 (45) 4053257
E-mail: p-van-rooijen@hotmail.com

Author:
Dr. Pieter van Rooijen

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1 Objectives

Between 1967 and 1975 the mines in the western and eastern mining regions of South Limburg were closed, starting with the Maurits mine in Geleen, and ending with the Julia mine in Eygelshoven (Fig. 1). 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, Dominiale, Willem Sophia, Laura, Julia, and Oranje Nassau I, II, III and IV) and four state-owned mines (Wilhelmina, Hendrik, Emma, and Maurits)

Due to the closing of the mines there was no longer any reason to continue pumping water to keep the mines dry. Step by step, the extraction of water in the mines was reduced. Most of the mines were interconnected, which meant that the reduction in extraction had to be carefully executed in order to not flood the remainder of the operating mines.

The mines that were still operational between 1967 and 1974 were protected from flooding by the construction of dams in mine corridors, which allowed a careful and controlled rise of the mine water. The German company EBV GmbH continued the extraction of mine water from the Beerenbosch II shaft on the Limburg side of the border and the Von-Goerschen Schacht, Gouley-Laurweg in Würselen (D), until 1994. The pumping was necessary to protect the German mines east of the Feldbiß fault from flooding.

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

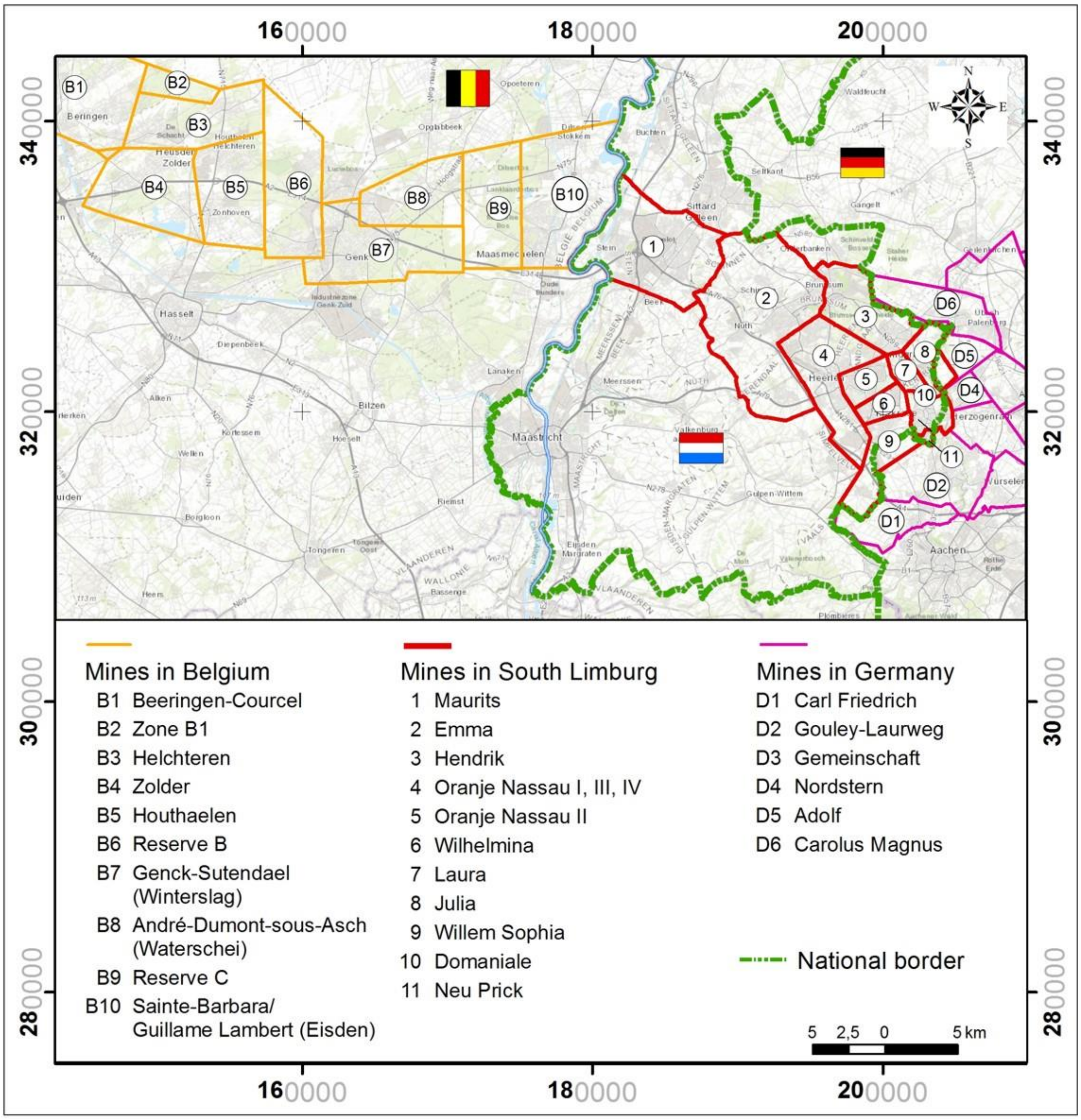


Fig. 1: Mines in South Limburg and adjacent areas of Belgium and Germany

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 the Beerenbosch II shaft. This caused the water level in the mines to rise gradually in large parts of Germany, South Limburg and Flanders.

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 effects of rising mine water levels have been studied before. In 1975 the Limburg province established a study group called “Hydrological consequences of the mine closures”. Based on the recommendations of this group, piezometers were drilled to monitor the rise of the mine water level and to track the water quality of shallow groundwater. In 1998 the state of affairs was reported and an initial prognosis was given about the expected effects of rising mine water levels.

More recently, research was done on the effects of rising mine water levels in the Netherlands. In 2011 Peter Rosner published his dissertation in which a lot of fundamental data was collected and analysed about the mining region and water in the mines (ROSNER, 2011). In 2007, the company Heitfeld-Schetelig (IHS), commissioned by the Ministry of Economic affairs, carried out a preliminary study on the effects of rising mine water.

2 Methodology

2.1 Introduction

In several preliminary studies it was found that the geohydrological system is highly complex; the coal deposits in the Carboniferous formation are present at the surface near the German border and drop down to greater depth in northwestern direction. In northwestern direction, on top of the Carboniferous formation there is a layer of increasing thickness consisting of sand, clay deposits and limestone (the overburden).

The faults present in the region and historic tectonic movement have caused the subsurface to differ greatly between locations. In some places permeable layers lie directly on top of the Carboniferous formation allowing water levels to rise in the overlying aquifers, by rising mine water. These locations will be referred to as “Hydraulic Windows” in this report. Hydraulic Windows sometimes occur naturally: some mines, such as the Maurits, were known as “wet mines”, because of the considerable volume of water which was seeping into the mine from the overburden (Fig. 2). In other places there are semi-permeable aquitards between the Carboniferous formation and the overlying aquifers. At these locations the rising mine water levels cause an increase in groundwater head (higher pressures) in the overlying aquifers, but no considerable upward flow of mine water.

Additionally, in areas where many upward and downward drillings were carried out, near faults, or where only a thin Carboniferous layer was left between mine works and the overburden, upwards flow of water may take place in the future.

Previous research also showed that predicting the effects of rising mine water was hampered by the lack of data on the mine water level in the Carboniferous formation. The mine water level is only measured in the eastern mining region (the Beerenbosch II and Willem II shafts in the Domaniale mine, shaft I Wilhelmina, shaft II Oranje Nassau I and shaft II in the Julia mine). In the mines from the Emma concession, in the Maurits mine, and in Belgium mines water levels are not measured.

Fig. 2: Water in mine Oranje Nassau IV (www.RHCL.nl)

In four locations however, the groundwater level is measured in the permeable limestone deposits in the overburden. Based on these measurements it is possible to get an indication of the effect of rising mine water levels on the overlying geological layers.

The lack of data is one of the reasons that previous research was mostly qualitative in nature. Additionally, in this period, no state-of-the-art 3D computer models were available which could quantify the effects of rising mine water and test different hypotheses concerning future developments as a result of rising mine water.

2.2 Problem statement

According to preliminary studies the following aspects were considered to be the most important effects of rising mine water and had to be investigated by WG 5.2.4 and WG 5.2.5:

- Wetting

Rising mine water can lead to an increase in groundwater level in the overburden. In regions with relatively high groundwater tables, such as the valleys in South Limburg, an increase 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 head in the deep aquifers, as well as the interaction between the deep aquifers and shallow groundwater.

- Change in groundwater quality

The composition of mine water is very different, compared to groundwater in shallow aquifers 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 aquifers and is mixed with water from shallow aquifers, several hydrochemical reactions will 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 like arsenic.

The occurrence of an upward flow of mine water, besides being dependent on the possible existence of hydraulic connections between the Carboniferous formation and the overburden, is also determined by the head 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 aquifers. Conversely, when the head in the Carboniferous formation is higher than the shallow groundwater head, groundwater quality in the overburden may be affected.

2.3 Risk assessment

2.3.1 General approach

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 analysis is engineered to show the scope of the possible effects: a "worst case" scenario describes how high the maximum mine water level rises. Hence, the fundamental assumptions for this scenario are worst case assumptions. For best "case scenarios" best case assumptions are made. Hence these best case scenarios yield lower calculated values for future mine- and groundwater levels. In the same manner an "average case" scenario was created which lies between these extremes. The average case scenario is also the "most likely" scenario.

The three scenarios are based upon a large amount of data which was gathered for this study by TNO and IHS and supplemented with literature reviews. Based on these data the system analysis was carried out. The analysis describes the complex stratification of the Carboniferous and its overlying layers.

After determining the three scenarios the conditions for the occurrence of each scenario was investigated. This analysis was carried out with 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 changing the quality of the groundwater and the increase in its level were investigated, and a proposal for appropriate monitoring is presented.

2.3.2 Determination potential wetting

Due to mine water rise, groundwater levels nearby mining areas can also rise. Areas were the groundwater levels were already high are most vulnerable for the rise of the mine water. Based on the surface level and the groundwater levels in the first aquifer, maps with the thickness of the unsaturated zone are elaborated. These maps are extended with land use areas like nature, urban areas, infrastructure and agriculture.

A groundwater model is used to estimate the effect of mine water rise on phreatic groundwater levels. Assumptions have to be made about the amount of mine water exfiltrating from the Carboniferous towards the shallow aquifers. These assumptions will be made upon measurements of mine water level over the past decades, since the mine water pumps stopped. The IBRAHYM-groundwater model is used to calculate the effects. First of all the current situation is calculated and evaluated. Subsequently, the estimated effect of rise of groundwater levels, due to mine water rise is evaluated.

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.

2.3.3 Determination potential change of groundwater quality

As indicated before hydro-geochemical reactions can occur along flow paths. Determining the location of hydraulic contacts in mining areas is important, both in the current situation, as in the future, under rising mine water conditions. To identify these contacts and their impact, several soil survey maps will be studied, such as maps with the top level of the Carboniferous formation, thickness and characteristics of covering layers, contact with shallow aquifers nearby, and characteristics of these shallow aquifers (permeability etc.). Furthermore, information is collected about the situation during mining activities. Were there specific circumstances during mining, which affected this hydraulic contact? Subsequently, the effect of mine water rise on the occurrence of these contacts is estimated.

Data considering the quality of mine water was collected. This was done for both the water from covering layers and the water from shallow aquifers nearby. Furthermore, information about possible reactive components in these aquifers is collected. Based on this information, a characteristic hydro geochemical situation is defined. The reactive transport model PHREEQC was used to calculate the effects of mine water entering the covering layers and on the groundwater quality of the aquifers in the overburden.

Based on the maps of expected groundwater quality and the recharge areas for groundwater extractions, the expected influence on the groundwater extracted by the Waterleiding Maatschappij Limburg or industry is estimated. Extent and nature of these risks are identified.

2.3.4 Bow-Tie-Analysis

In this study the Bow-Tie-Analysis is used as the method to analyse the risks per after-effect, to create possible impact maps, define mitigation and prevention measures.

Bow-Tie-Analysis is a strong tool to visually clarify the risks and map measures associated with the effects or hazards. The power of a BowtieXP diagram is that it gives an overview of multiple plausible scenarios in a single picture.

Fig. 3 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 the incident are summarised, i.e. the Threats. On the right side, the potential impacts from the Top Event are listed, i.e., the Consequences.

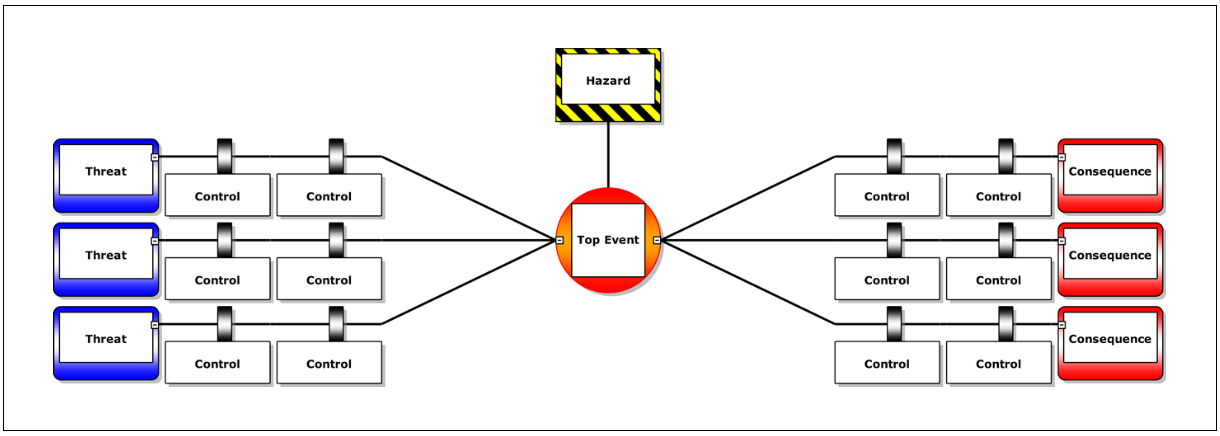


Fig. 3: Schematic representation of a Bow-Tie-Analysis

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

3 Hydrogeological system of the basement

3.1 Introduction

The mining district of South Limburg is located on the northwestern flank of the great tectonic unit Venn Anticline. Due to the tectonic compression numerous SW-NE striking anticlines and over thrusts occur (from NW to SE: anticline of Puth, 70 m fault, anticline of Waubach/Oranje fault, Willem fault), which are of importance for the structure of the Carboniferous bedrock and the distribution of mine workings (Fig. 4).

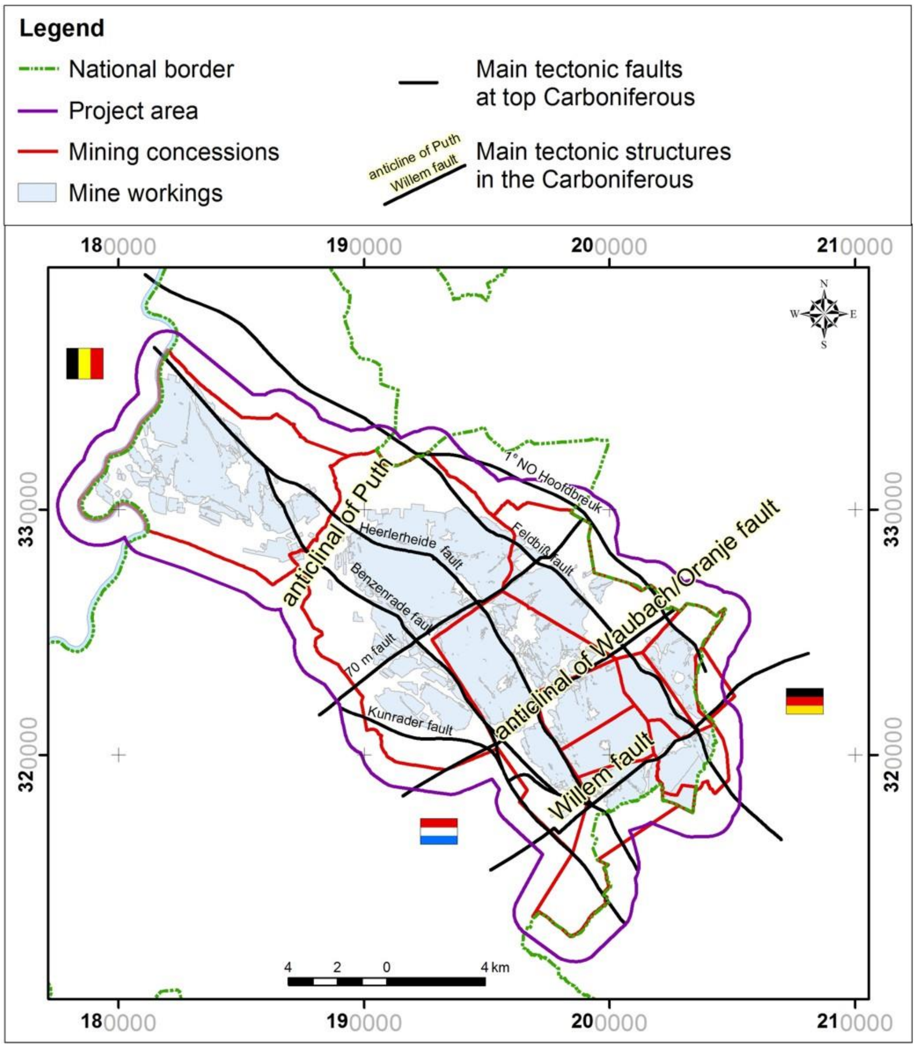


Fig. 4: Main tectonic structures of the Carboniferous basement

Almost perpendicular to these old tectonic structures, there is a system of three main NW-SE orientated faults: the Benzenrade fault, the Heerlerheide fault, and the Feldbiß fault (Fig. 5). These faults run through the overburden to the surface and divide the study area into three main hydrogeological units (HYI/HYII/HYIII, HYIVb in Fig. 5).

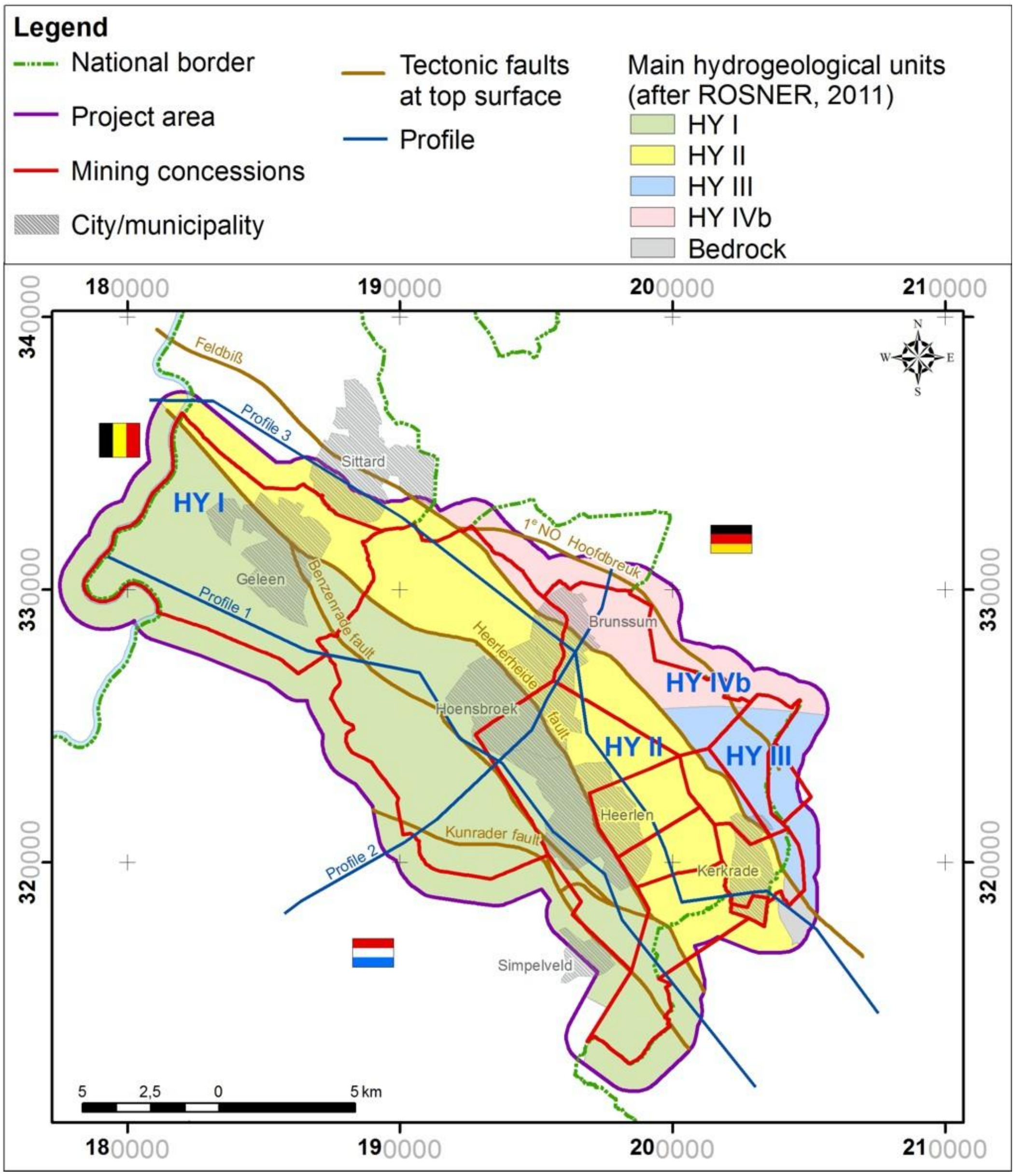
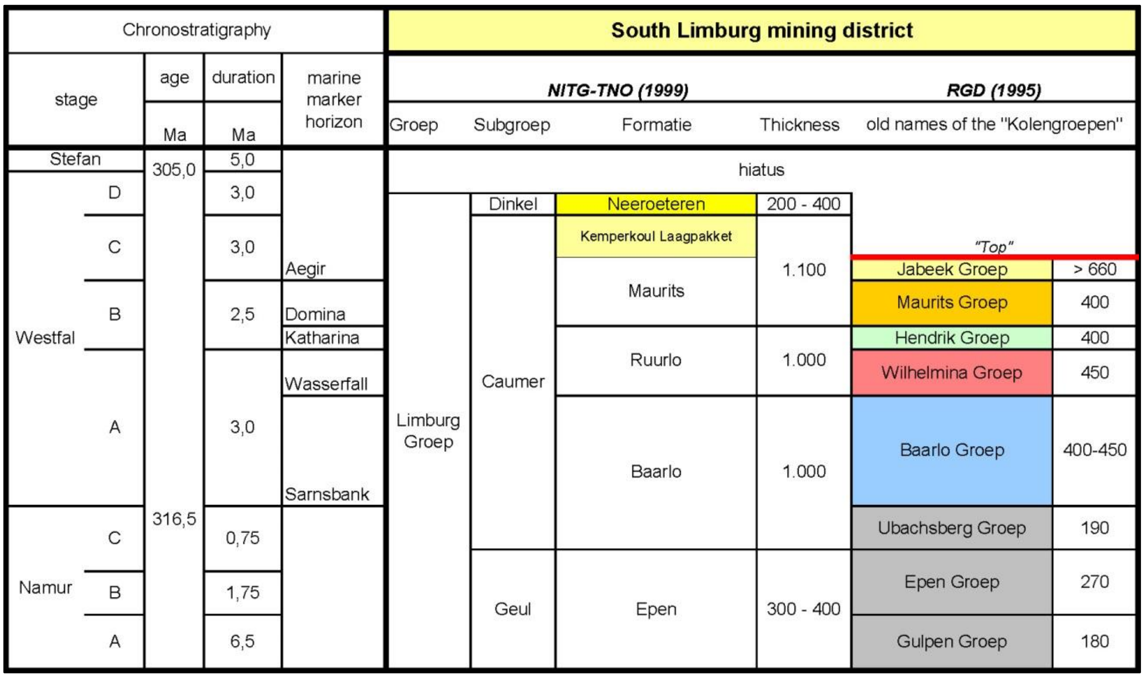


Fig. 5: Main fault zones and hydrogeological units

3.2 Hydrogeological structure of the basement

The relevant part of the basement for this study consists of the coal-seam-bearing part of the Upper Carboniferous (Westphalian A to C, Jabeek, Wilhelmina, Hendrik and Maurits Groep). The overall thickness is about 2.000 m. Fig. 6 shows the stratigraphy of the basement in the study area.



Chronostratigraphy					**South Limburg mining district**					
					NITG-TNO (1999)				*RGD (1995)*	
stage		age Ma	duration Ma	marine marker horizon	Groep	Subgroep	Formatie	Thickness	old names of the "Kolengroepen"	
Stefan		305,0	5,0		hiatus					
Westfal	D		3,0		Limburg Groep	Dinkel	Neeroeteren	200 - 400		
	C		3,0	Aegir		Caumer	Kemperkoul Laagpakket	1.100	"Top"	
							Maurits		Jabeek Groep	> 660
	B		2,5	Domina					Maurits Groep	400
				Katharina			Ruurlo	1.000	Hendrik Groep	400
				Wasserfall					Wilhelmina Groep	450
	A		3,0	Sarnsbank			Baarlo	1.000	Baarlo Groep	400-450
Namur	C	316,5	0,75						Ubachsberg Groep	190
	B		1,75			Geul	Epen	300 - 400	Epen Groep	270
	A		6,5						Gulpen Groep	180

Fig. 6: Stratigraphy of the basement in the South Limburg mining district (ROSNER, 2011)

It is a cyclic sequence of predominantly shale, claystones and sandstones with coal seams. The layers of Namur and Westphalian as a whole are classified as groundwater aquitards, if they are not fractured by the mining activities. Although there is an increased permeability within well fissured sandstones, these sandstones do not have a connection to a regional groundwater flow system.

The coal-seam-bearing Upper Carboniferous ends with an extended eroded layer. The formations overlying the Carboniferous (Cretaceous, Tertiary, Quaternary) consist of various layers with varying thickness, distribution and hydrogeological characteristics.

Below the coal-seam-bearing Upper Carboniferous lies 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 aquifer.

The surface of the Carboniferous formation and the oldest layers of the overburden slope gently downwards, generally at about 1° to 2°, in a northwestern direction. 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 northwestern direction are shown in Fig. 7 and Fig. 8. The offset of the top of the Carboniferous bedrock at the main tectonical fault to the NE is shown by profile 2 in Fig. 9.

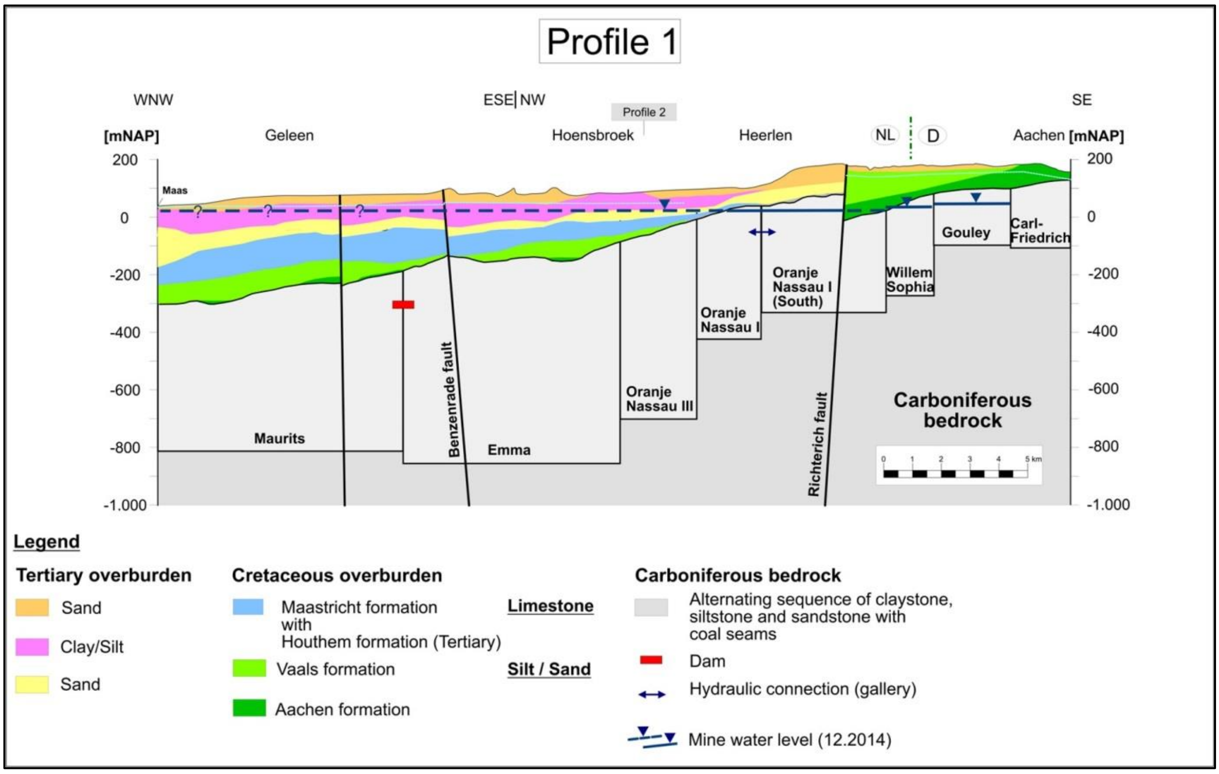


Fig. 7: NW-SE cross-section profile 1

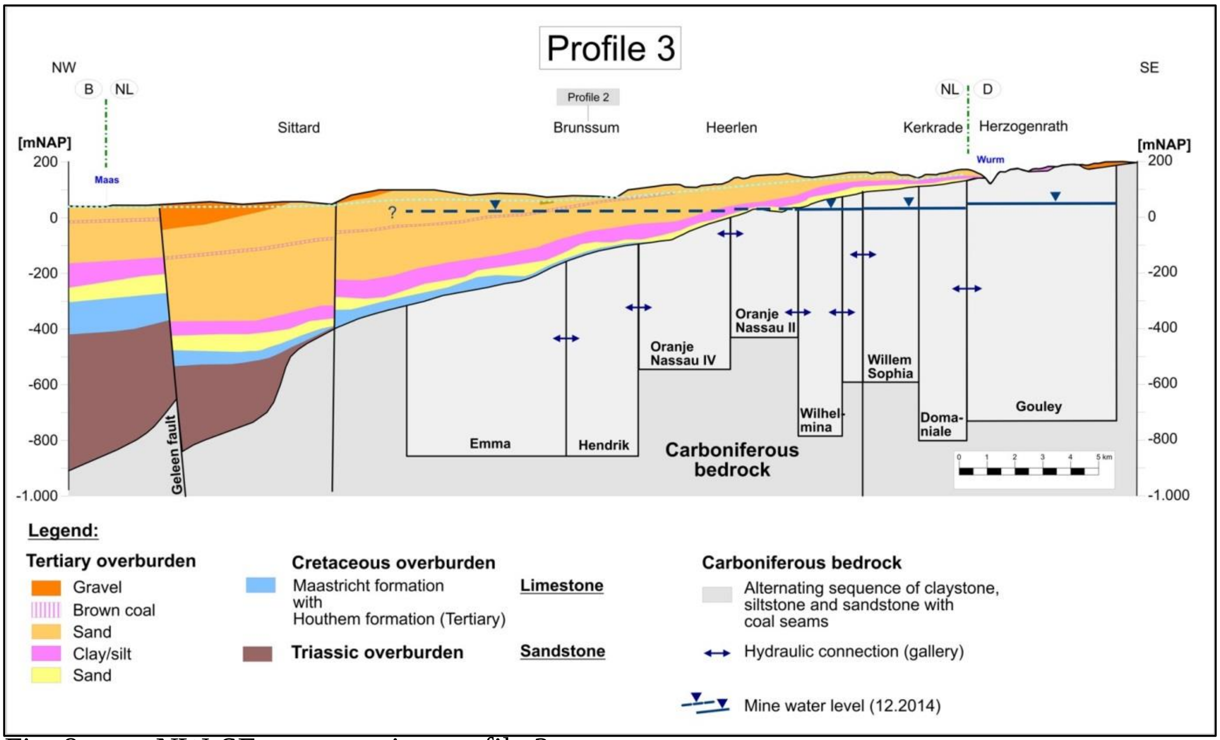


Fig. 8: NW-SE cross-section profile 3

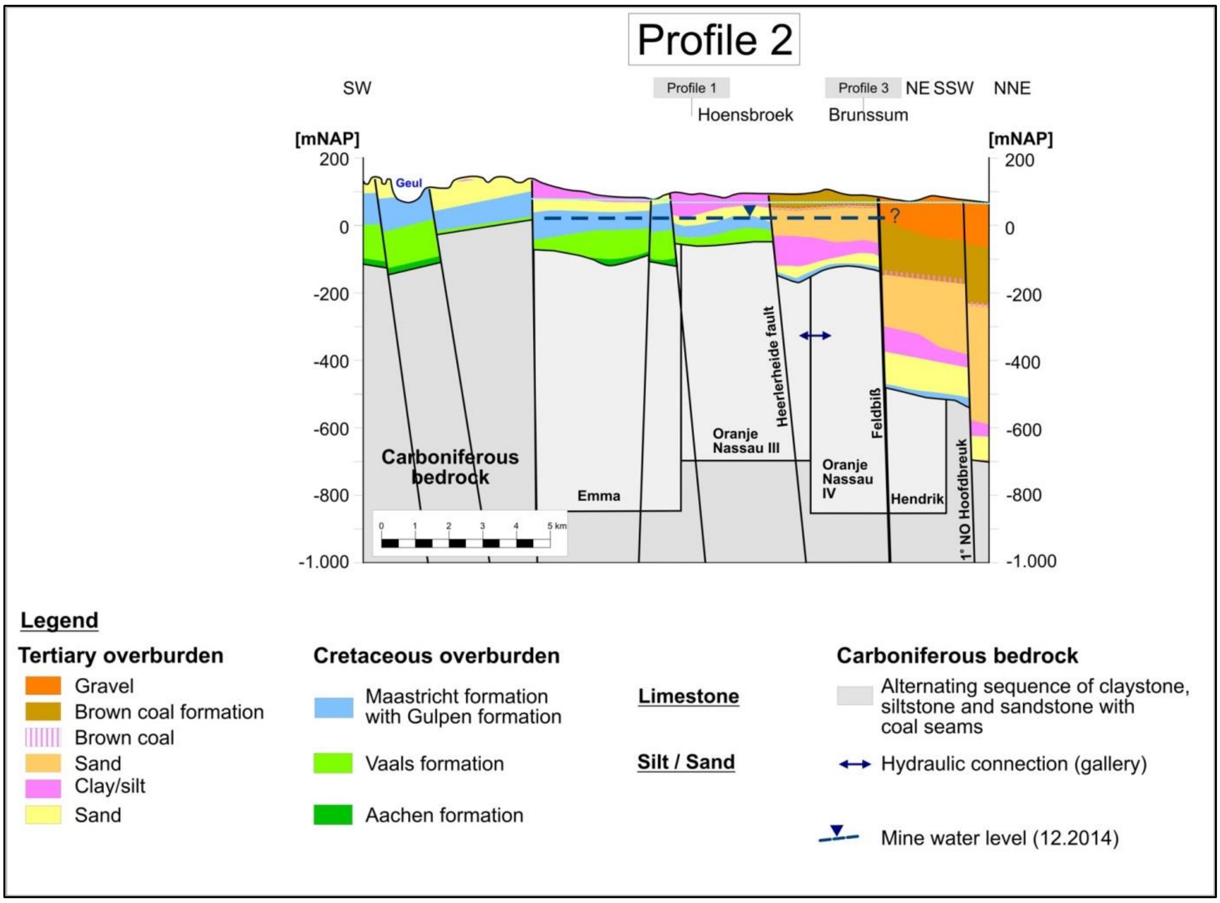


Fig. 9: SW-NNE cross-section profile 2

3.3 Top Carboniferous (TC)

3.3.1 Database

There are several sources of data from which the depth of the surface of the Carboniferous formation can be estimated:

- a well-documented map by PATIJN (1961),
- the Regional Geohydrological Information System REGIS-II v2.1 and the subsequent update in 2015 performed by TNO for the project (REGIS-II v2.2),

- maps of mine shafts and corridors, and analysis of drillings, both downward drillings (used in the period that mines were operational to determine the depth of the Carboniferous layer) as well as upward drillings. The drillings were performed to determine where the Carboniferous should not be excavated as a safety precaution to prevent the collapse of mining corridors,
- a map of the Top Carboniferous (TNO, 2015).

Analysis of the data shows that there are significant local differences in the presumed elevation of the Top Carboniferous. Especially where the Carboniferous formation is found at a larger depth (generally between faults), the maps produced by PATIJN (Fig. 10) show different elevations than REGIS-II v2.1 and REGIS-II v2.2, or the more recent map by TNO (Fig. 11). Furthermore it has to be considered that the REGIS model shows the “hydrogeological basis”, which is not equivalent to Top Carboniferous in the places where the Triassic formation occurs (Fig. 8).

VAN ROOIJEN (2015) performed a detailed analysis of the differences in interpretation of the Top Carboniferous and identified local differences of the Top Carboniferous according to PATIJN and REGIS (Appendix 1).

In this investigation it was decided not to elaborate the REGIS model/groundwater model IBRAHYM according to the remarks of VAN ROOIJEN, because the relevance for the groundwater modelling itself was limited.

However, it is advised to take notice of the remarks delivered by VAN ROOIJEN, when the groundwater model IBRAHYM, which is based on the REGIS-II v2.1 model, is updated in the near future.

The remarks from VAN ROOIJEN (2015) to the REGIS-II v2.1 model are presented in Appendix 2.

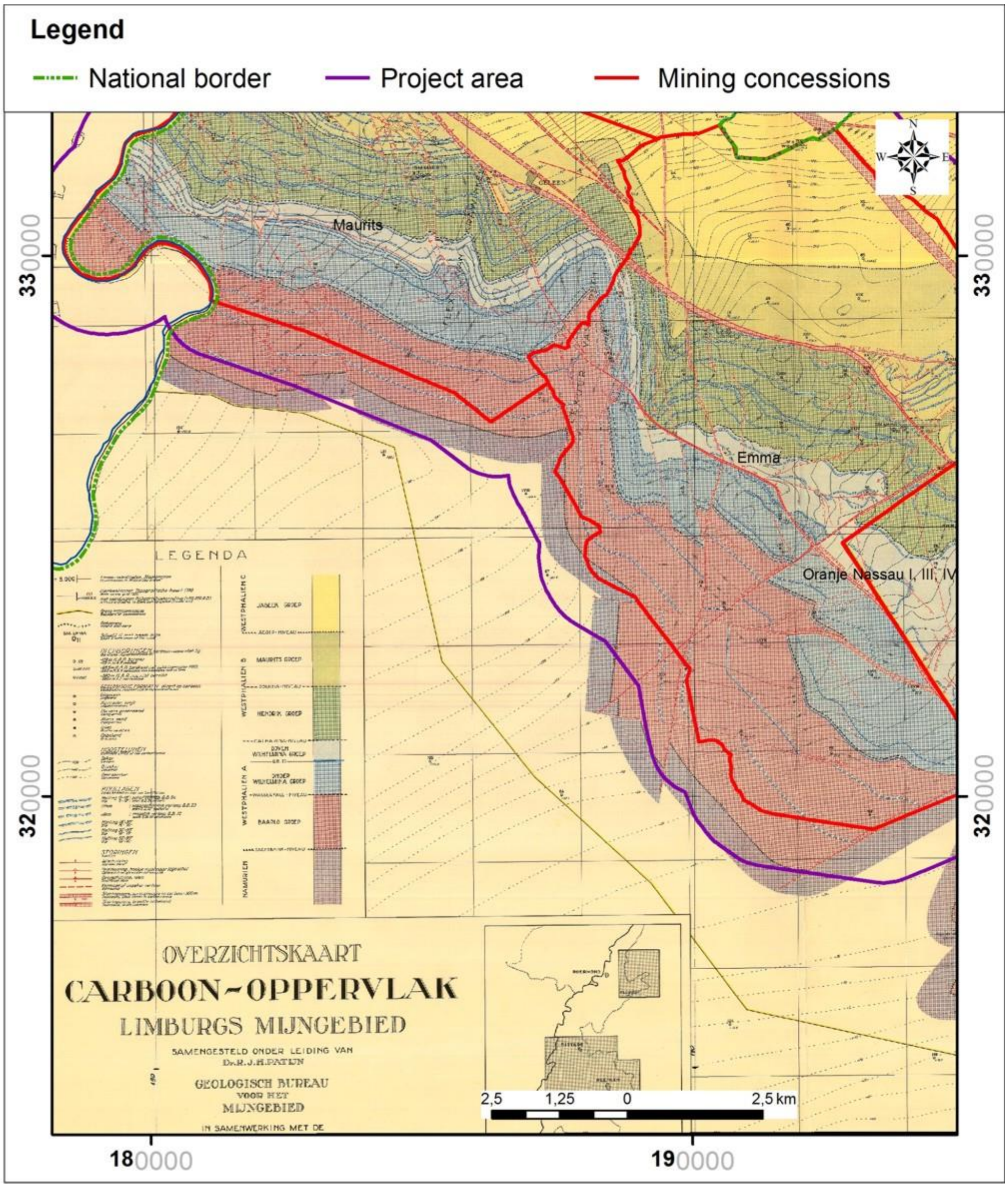


Fig. 10: Top of Carboniferous formation (TC) according to PATIJN (1961)

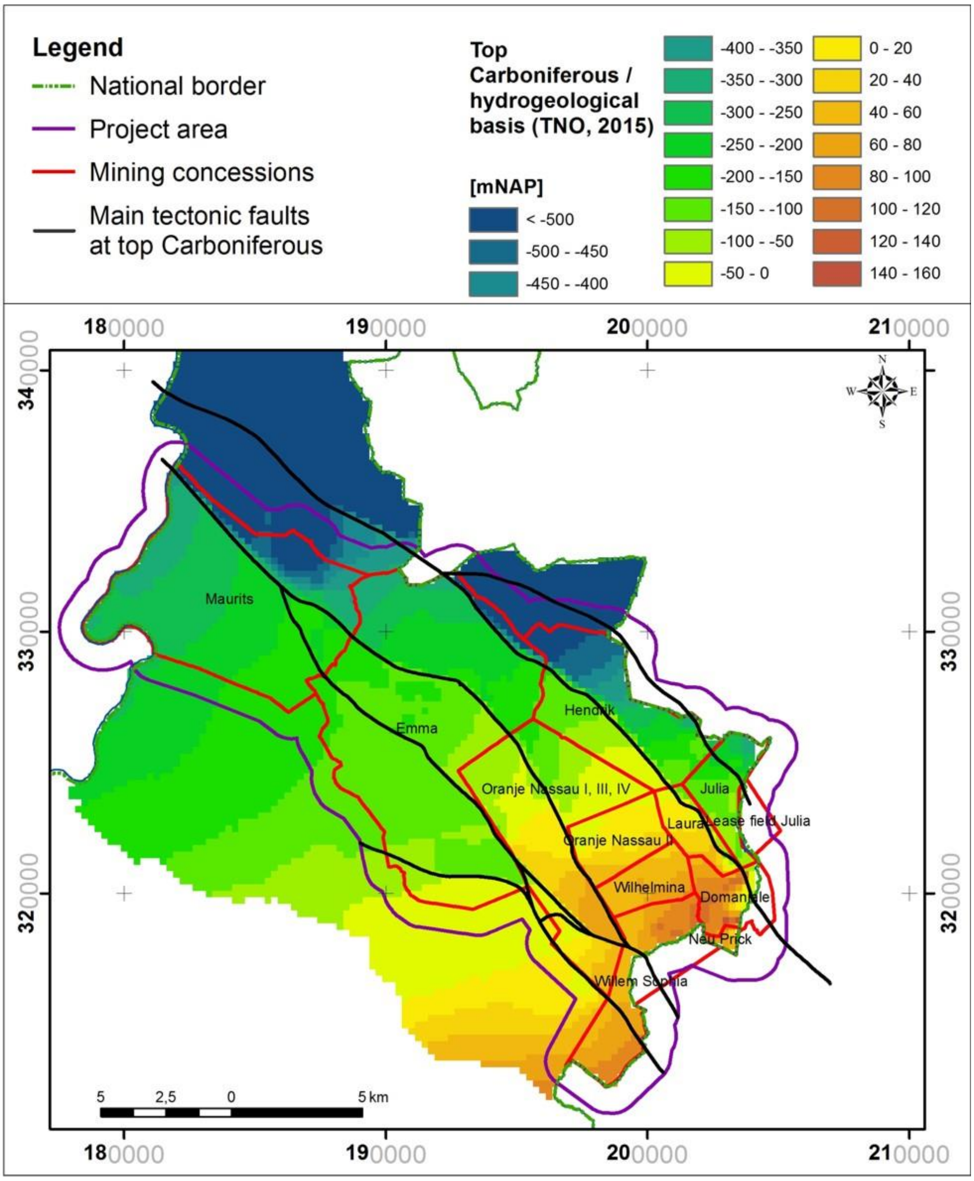


Fig. 11: Top Carboniferous/hydrogeological basis according to TNO (2015)

3.3.2 Structure and covering strata

The calculation of the effects of rising mine water was performed using the IBRAHYM groundwater model. For the calculations it was important to determine the elevation of the Carboniferous formation, the thickness of the remaining coal deposits and the aquitards lying directly on top of the

Carboniferous formation. This was especially important because IBRAHYM is based on the REGIS-II v2.1 and not on the updated REGIS-II v2.2.

In the figures below the geohydrological layers overlaying the Top Carboniferous are shown on the basis of REGIS-II v2.1.

Southwest of the Heerlerheide fault, the Top Carboniferous is overlaid by the Aachen formation and/or the Vaals formation (Fig. 12, Fig. 13). There are only a few small “windows” in this cover where limestones from the Maastricht formation directly overlie the Carboniferous (Fig.14).

Northeast of the Heerlerheide fault the Maastricht formation, consisting mostly of limestones and marls, overlies the Top Carboniferous in the central part of the project area (Fig. 14). In the southeastern part of the investigation area, near Heerlen, a complex of sand, silt and clay belonging to the Tongeren formation, is found on top of the Carboniferous bedrock (Fig. 15). In the northwestern part, northwest of the anticline of Puth and outside the mined area, Triassic sediments form the basis of the overburden (Fig. 8).

3.4 Hydraulic situation in the mining areas

The South Limburg mining district builds the central part of the coal mine region that reaches from the Aachen area in Germany in SE to the Hasselt/Beringen area in Belgium to the NW (Fig. 1). Along the borderlines (Maas river and Wurm river valley) hydraulic interactions have to be considered. Within the South Limburg mining district a complex hydraulic system has developed after closure of the mines.

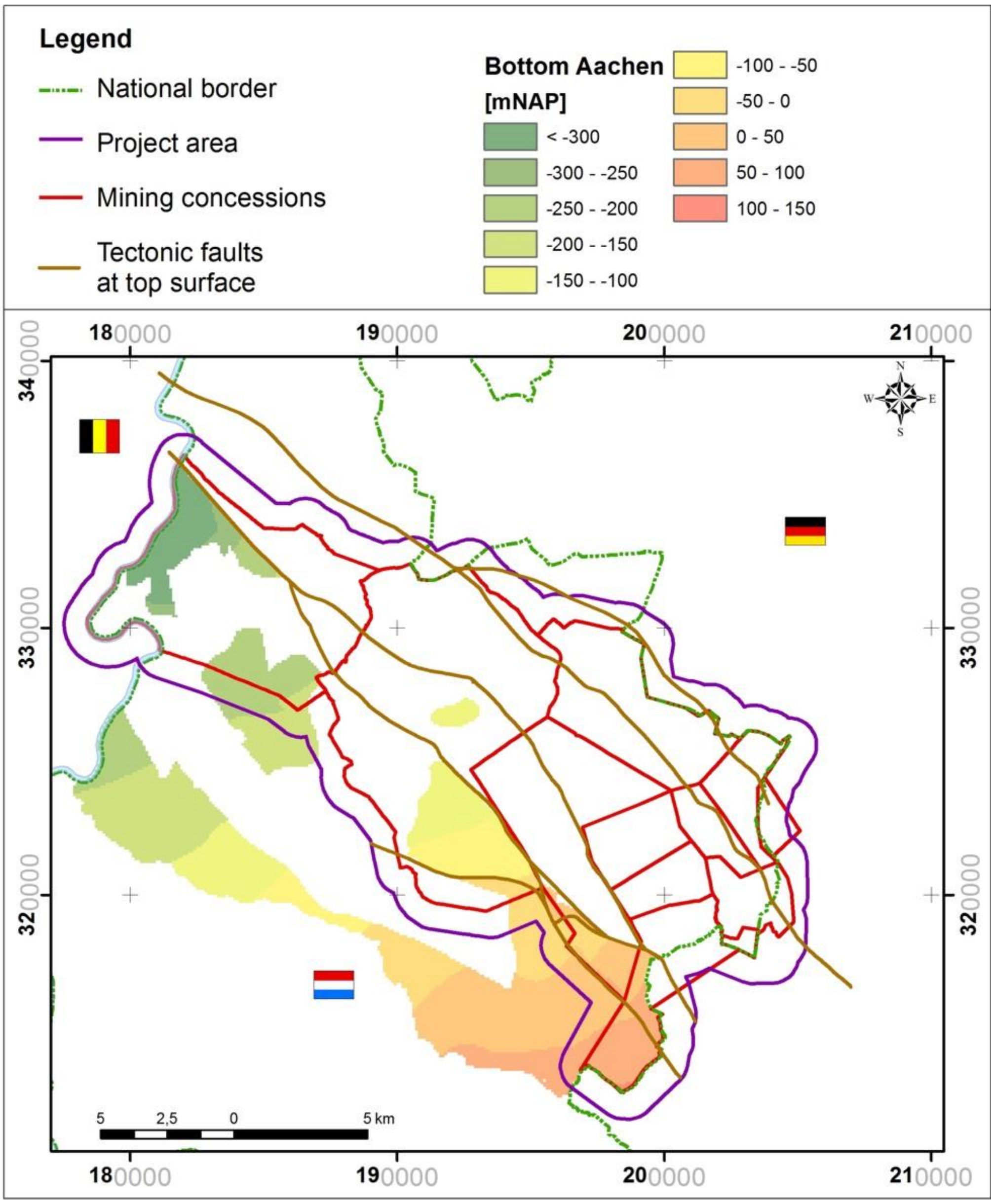


Fig. 12: Aachen formation on top of Carboniferous (REGIS-II v2.1)

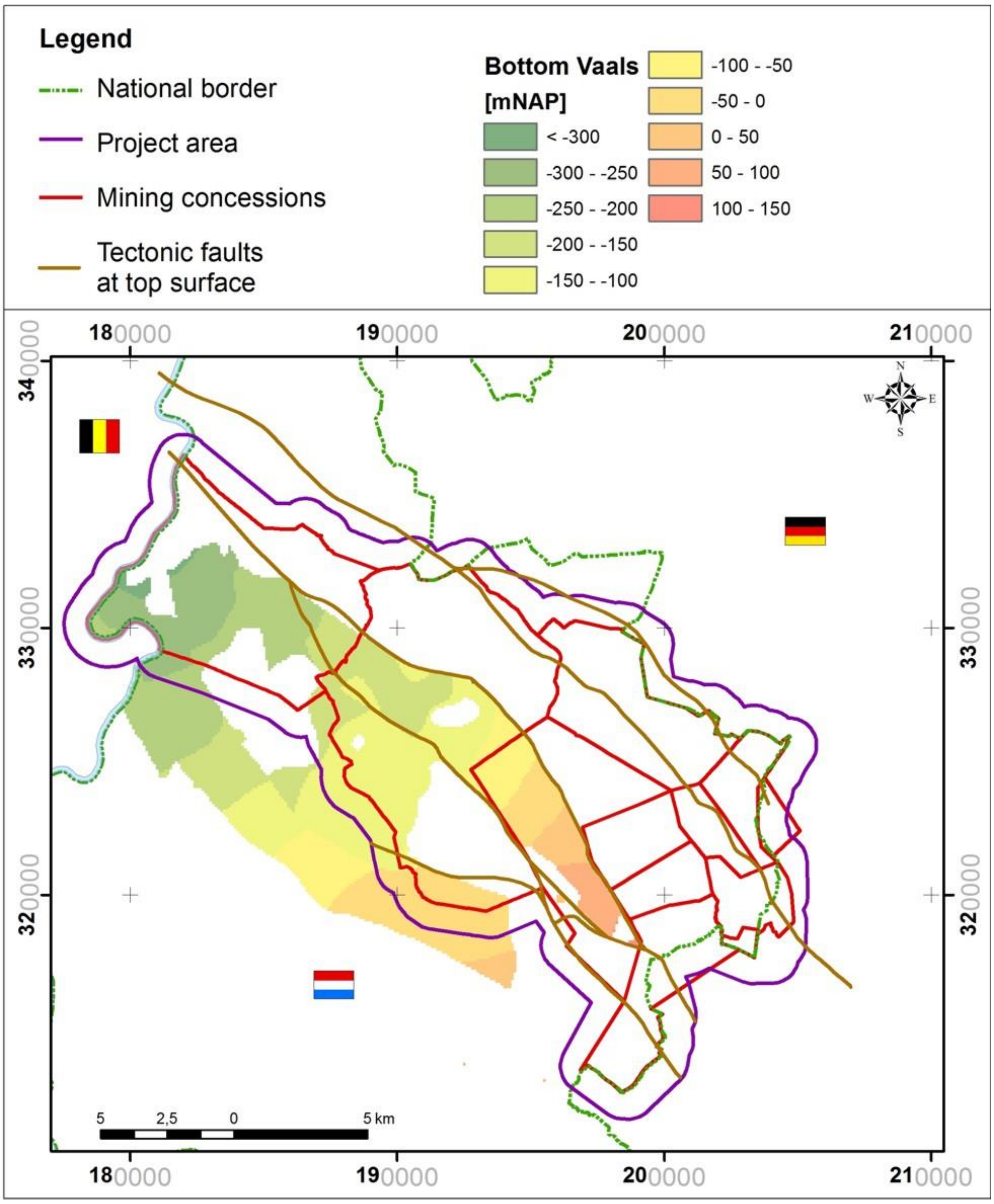


Fig. 13: Vaals formation on top of Carboniferous (REGIS-II v2.1)

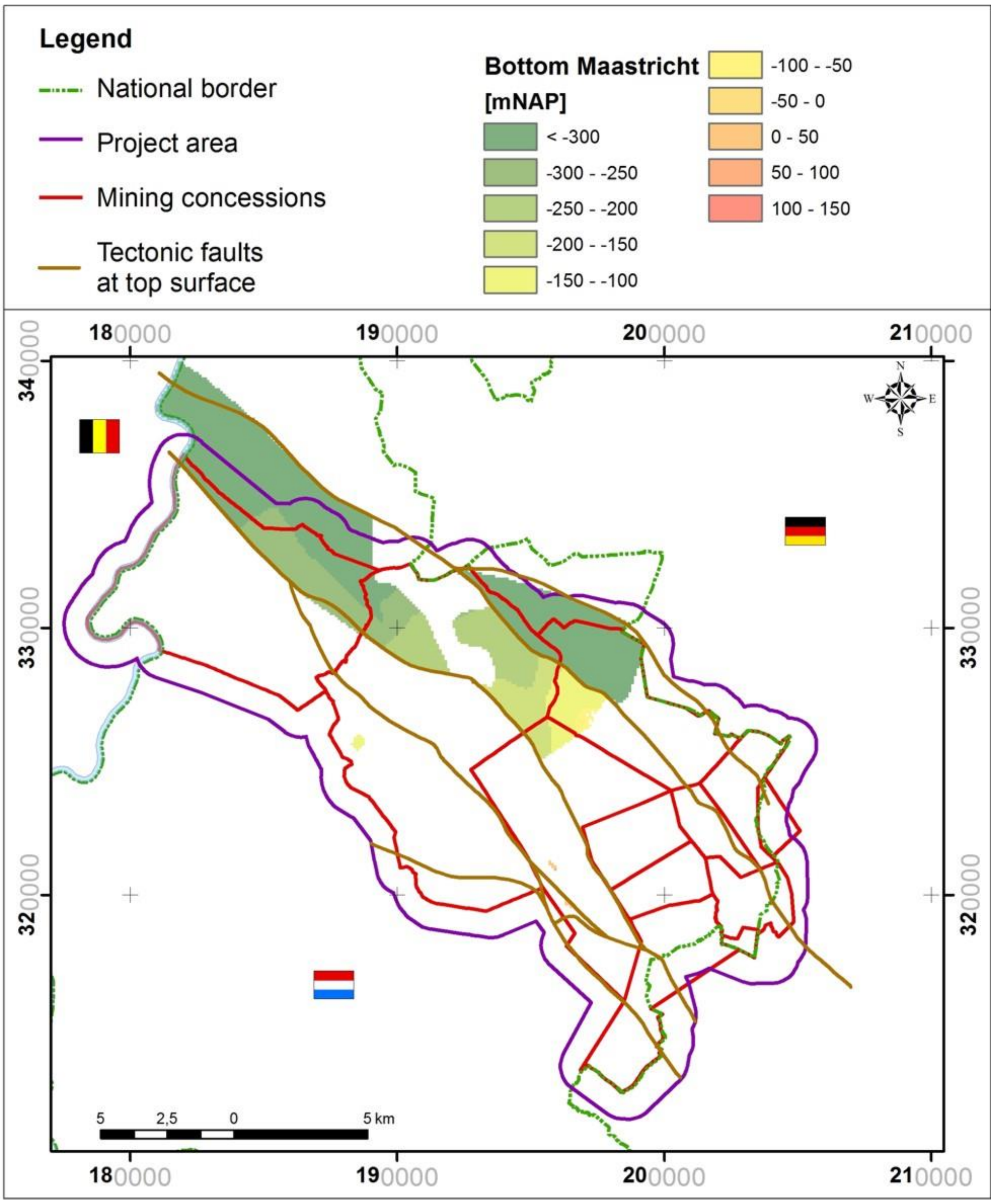


Fig. 14: Maastricht formation on top of Carboniferous (REGIS-II v2.1); northwest of the anticline of Puth the Maastricht formation is underlain by Triassic sediments

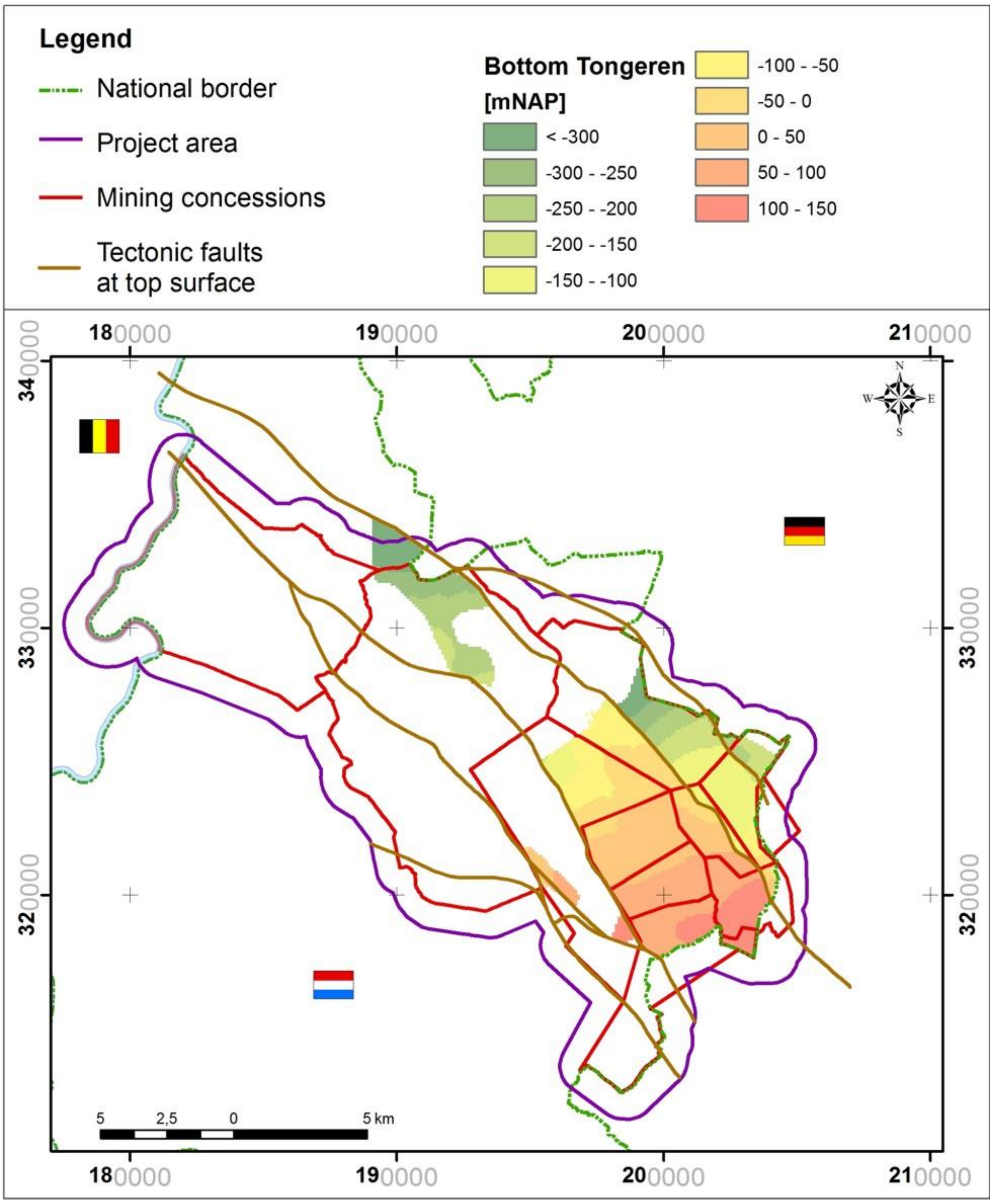


Fig. 15: Tongeren formation on top of Carboniferous (REGIS-II v2.1)

3.4.1 Hydraulic connections between mine workings in South Limburg

All the Dutch mining areas were more or less connected by underground works. It is assumed that the mined layers have a permanently higher hydraulic conductivity than the unmined bedrock.

Due to the tectonical structure of the Carboniferous only parts of the concessions were mined. Especially in the area of the anticline of Puth between the Maurits and Emma mines there is a mining gap (Fig. 4). As a result, this area has a lower hydraulic conductivity than the mined area, and can be regarded as a hydraulic barrier within the South Limburg mining district.

During the closure of the mines the hydraulic connections between the mines have been closed especially in the deeper levels. In particular the connecting gallery between Emma and Maurits and the galleries across the Feldbiß fault to the mine workings of Hendrik mine northeast of the Feldbiß fault were closed. Therefore these mining areas are now hydraulically isolated basins in the level of the Carboniferous.

Fig. 16 shows that the Maurits and Emma mines once were connected to each other by an approximately 11,5 km long gallery at a depth of 390 m. After the closure of Maurits mine this gallery was sealed by a “dam door”.

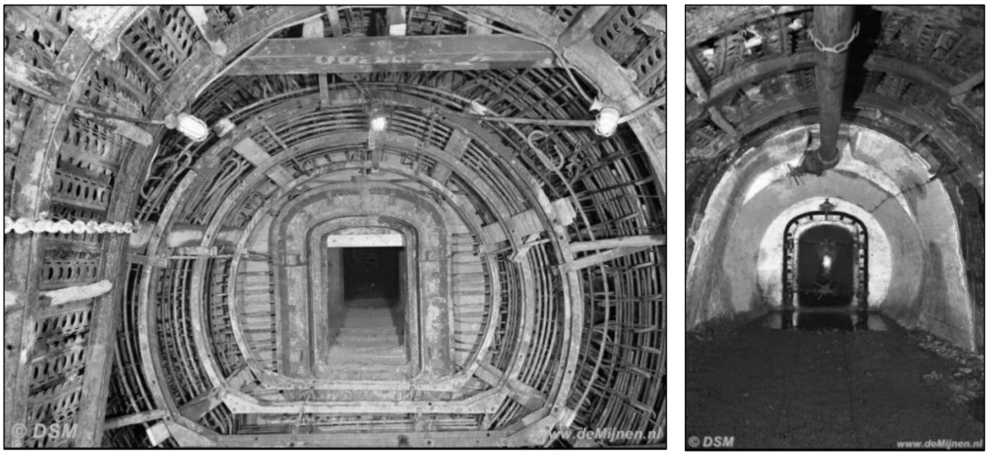


Fig. 16: Gallery between the Emma and Maurits concessions

All the other mines of the South Limburg mining district are still connected to each other at different levels. There are some main galleries that connect the former mines and create a system of several main basins that interact hydraulically with one another (Fig. 17).

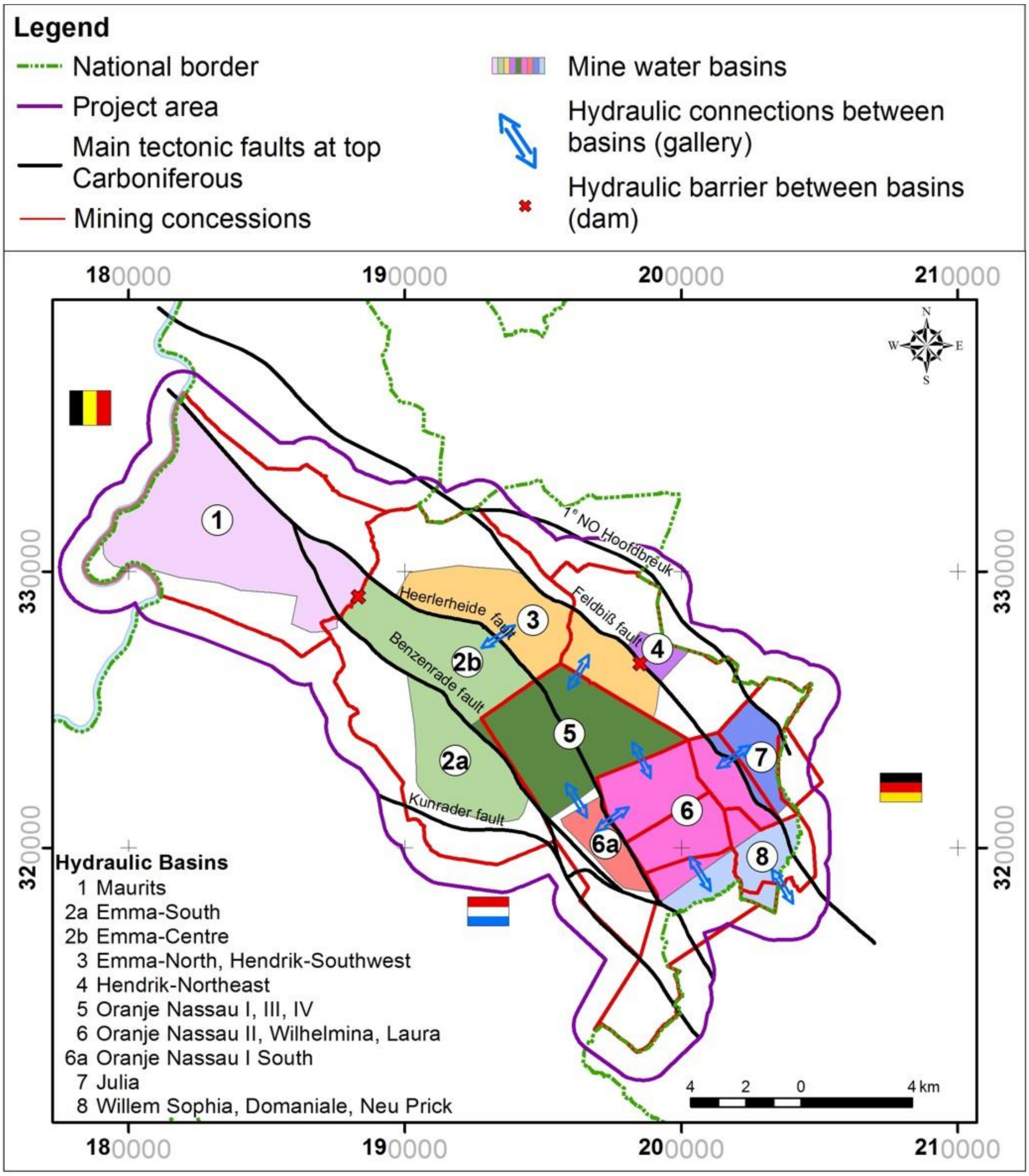


Fig. 17: Hydraulic structure of the South Limburg mining district

3.4.2 Hydraulic connections between German and Dutch mines

Due to the historical development the Dutch mines are quite close hydraulically connected via galleries and mine workings to the German Gouley-Laurweg mine, which is located along the Wurm river valley in the Southwest of the Feldbiß fault. Therefore mine Gouley-Laurweg together with the mines in South Limburg form a hydraulically connected “western mine water province”. The further German mines, which are all located northeast of the Feldbiß fault (“eastern mine water province”), have no direct connection to the Dutch mines or the Gouley-Laurweg mine.

But there are some locations where a hydraulic connection could theoretically exist between Dutch and German mines northeast of the Feldbiß fault. These are three known locations at a depth of -123, -207 and -162 mNAP where the distance of single mine workings or galleries of Dutch and German mines is reduced to a few metres only.

However, since the water level in the German mines northeast of the Feldbiß fault in the year 2009 was approximately 100 to 110 m lower than that in the Dutch mines, it seems quite evident that there is almost no mine water flow across the Feldbiß fault into the German mines. This is not expected to change in the future. However, a flow of mine water across the border and the Feldbiß fault in the overburden via the Tongeren formation has to be considered.

On the German side of the Wurm three former dewatering galleries to the Wurm river were reopened to drain future mine water into the Wurm. According to the mine water concept of the responsible German mining company further former mining galleries will be opened if the mine water should reach the Wurm level to restrict the rise of the mine water level to the level of the Wurm river. Therefore, the rise of mine water in the German mining district will be limited to about

110 mNAP along the Dutch-German borderline. That is also the lowest level of the river Wurm in the area where the Carboniferous reaches the surface.

3.4.3 Hydraulic connections between Dutch and Belgian mines

On the west side of the river Maas Belgium also mined coal till 1992. According to the information acquired within this project there is no hydraulic connection between the Maurits concession and the adjacent Belgian mine Eisden on the other side of the river Maas. Nevertheless the hydraulic interactions in the level of the overburden (limestone) have to be considered.

3.5 Hydrochemical characteristics of the mine water

Deep groundwater is characterised by a higher mineral content than near-surface groundwater. The main reason for the high mineral content is the high NaCl-content, which can reach up to 300 g/l through dissolution of salt deposits. Lower mineral contents of up to 30 g/l NaCl often occur due to fossil seawater inclusions (connate water). Highly mineralised water typically rises along specific flow paths in thermal water springs (e.g. the thermal springs in Aachen) or along faults.

The groundwater in the study area is characterised by an increasing degree of NaCl mineralisation at increasing depths. KIMPE (1963) and ROSNER (2011) described five different types of groundwater mineralisation with smooth transitions. Tab. 1 shows the average mineral content in 1992, 1993 and 2009 in the basement of the South Limburg mining district (ROSNER, 2011).

The differences in inflow from the overburden led to different degrees of the “sweetening” of mine water in the concessions (see Fig 19).

Tab. 1: Overview of the average mineral content of mine water

Concession (shaft)	Year time	Electr. conductivity [µS/cm]	Chloride [mg/l]	Sulphate [mg/l]	Iron [mg/l]	Calcium [mg/l]
Maurits	operation		3.000			
Oranje Nassau I	operation		7.660*			
Domaniale (Beerenbosch II)	operation		510			
	1992/93	9.000	2.700*	300	12	400
	2009	1.750	200	300		10
Gouley-Laurweg (Von-Goerschen)	operation		90-150			
	1992/93	1.700	100	80	0,5	1750
	2009	1.900	200	300**		70

* Inflow from deep thermal water, probably along faults
** increasing FeS weathering

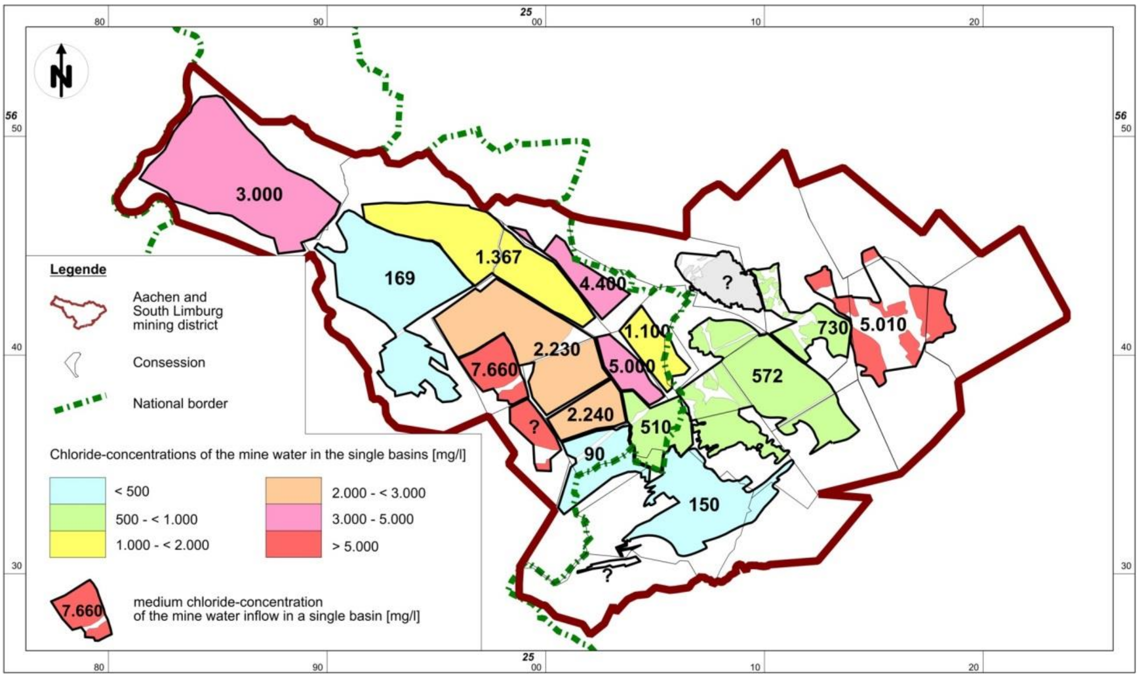


Fig. 18: Average chloride-concentrations in the different mine waters (ROSNER, 2011)

There is a trend towards a lower mineral content in the southeast of the study area, where the overburden is thinner and sometimes missing completely. Contrary to this trend, the mining concessions Oranje Nassau I North (and probably also the more south-east mining concession Oranje Nassau I South) had an average chloride content of 7.660 mg/l due to the inflow of thermal water.

This inflow of thermal water occurred in the Oranje Nassau I South mine at a depth of about 250 m below the surface (KIMPE, 1963). Initially, the outflow of saline thermal water (50° C) was up to 7 m^3/min but later dropped to 2 m^3/min. In 1960 the flow path was sealed off. The rise probably occurred along one of the NW-SE faults. The inflow was 4 to 15 % of the total inflow.

The NaCl concentration of the thermal water was about 35 g/l. The water probably rose from a depth of 1.300 to 2.800 m from the Kohlenkalk (Lower Carboniferous). KIMPE (1963) described this occurrence near Benzenrade along the Grondgalerij Laag VI fault as a local upward inflow of saline water from greater depths. Further occurrences of ascending thermal water are also reported from Wilhelmina (16 g/l NaCl at a depth of 700 m) and Oranje Nassau IV (12 g/l NaCl at a depth of a 420 m).

3.6 Hydraulic system in the operation period

The total inflow during the active mining period was estimated with the historic data gathered by ROSNER (2011) and reached up to 48 m^3/min. Groundwater flow towards the mining area is the result of three “driving forces” (Fig. 19):

- direct groundwater recharge in zones without overburden (four blue arrows);
- groundwater leakage through the overburden while there is still a downward gradient (blue arrow);
- rising of thermal water (red arrow).

If the inflow of thermal water (max. 7 m^3/min) in Oranje Nassau I is subtracted from the total inflow, there is still an inflow of approximately 40 m^3/min, which originates from the overburden.

In the southeast the inflow was and still is significant. Consequently, the concentration of minerals is low (90 mg/l chloride (Willem Sophia) up to 510 mg/l chloride (Domaniale)). The main cause is the thin and locally absent overburden. The area with only thin cover or absence of overburden in the southeast is about 14 km^2. There is also an additional flux from infiltrating water from the Wurm and the floodplains of the Wurm, which cannot be quantified.

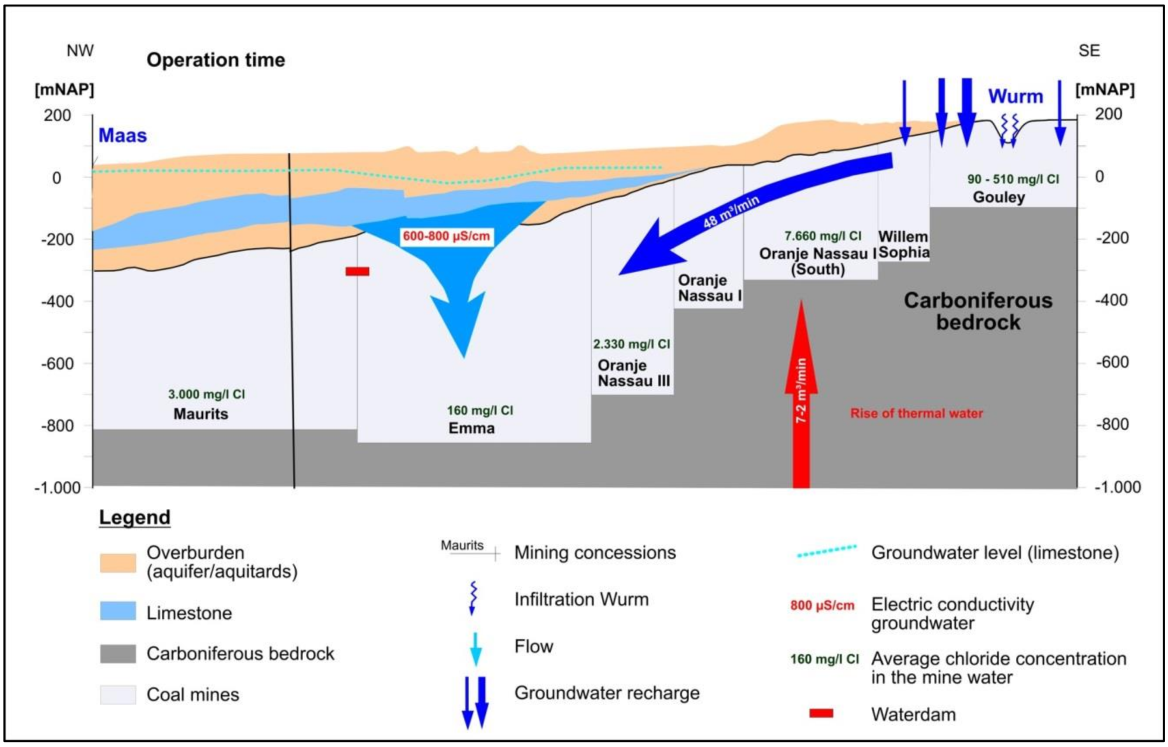


Fig. 19: Groundwater inflow and average mine water salinity during operation time (shown schematically)

In the northwest, where the overburden is quite thick, the inflow was about half of the average groundwater recharge. In summary, the level of groundwater recharge can be used to subdivide the area into three general groups, with high levels in the southeast and low levels in the northwest (ROSNER, 2011):

- Wilhelmina/Laura: 6,0 - 6,3 l/s/km^2
- Oranje Nassau II, III, IV, Emma/Hendrik: 2,7 - 4,8 l/s/km^2
- Maurits: 1,4 l/s/km^2.

The general development of mine water quality is influenced by several major processes:

- decrease of the mineral content by push back of deep thermal water,
- increase of sulphate weathering,
- decrease of the mineral content by inflow of fresh groundwater from the overburden,
- future leaching of salt in the submerged mines.

Based upon the mechanisms above, it can be expected that - due to the oxygen-rich groundwater supply from the overburden - the oxidation of pyrite will increase. As a consequence the pH-value will decrease and the sulphate level and the solubility of heavy metals will increase. Overall, the mineral content of water in subsequent decades is expected to be significantly lower than the mineral content during the mining period. It is likely the recognisable trend of hydrochemical stratification will continue in the future with heavy salt water settling at the greatest depths.

3.7 Mine water level rise until the present day

The rise of mine water in the “western mine water province” (South Limburg mines with Gouley-Laurweg) occurred in two distinct phases (Fig. 20, Fig. 21):

- The shutting down of the mines between 1967 and 1974 and the subsequent rise of mine water with the exception of the mine areas Domaniale and Gouley-Laurweg (D).

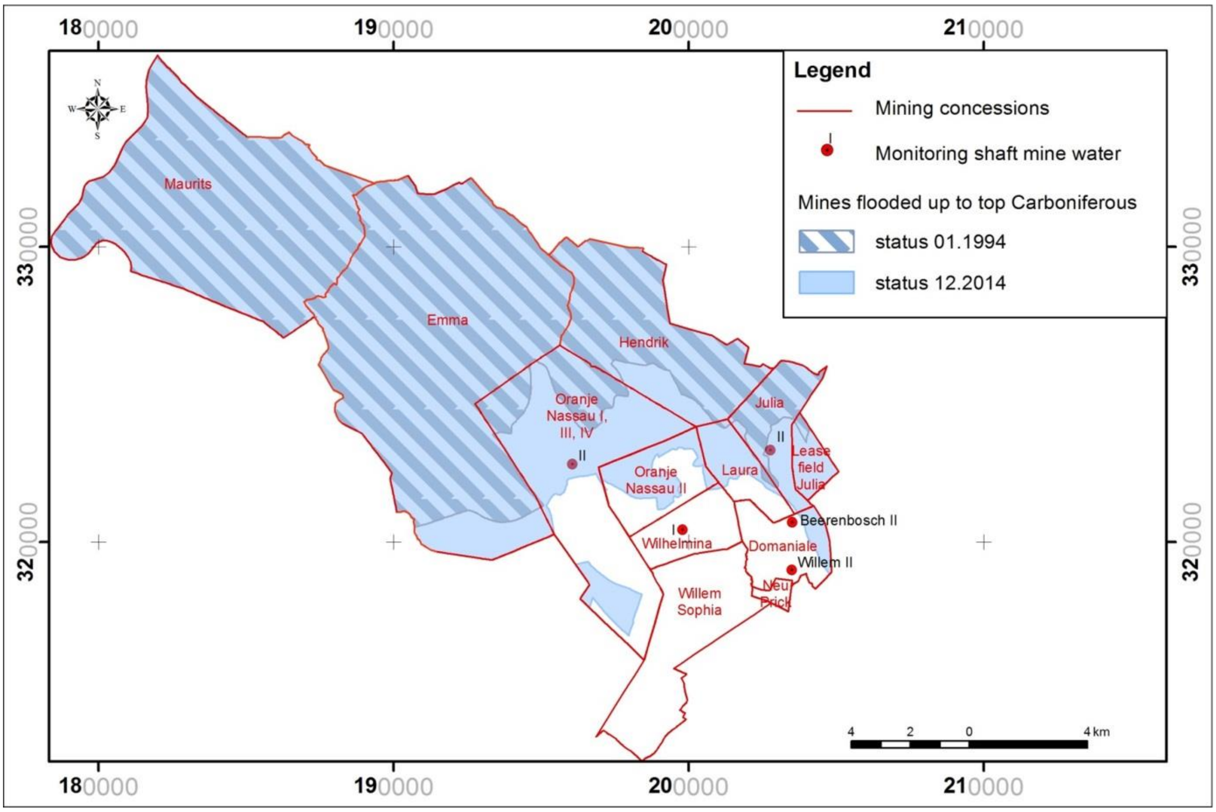


Fig. 20: Flooded areas in the Dutch mines in 1994 and 2014

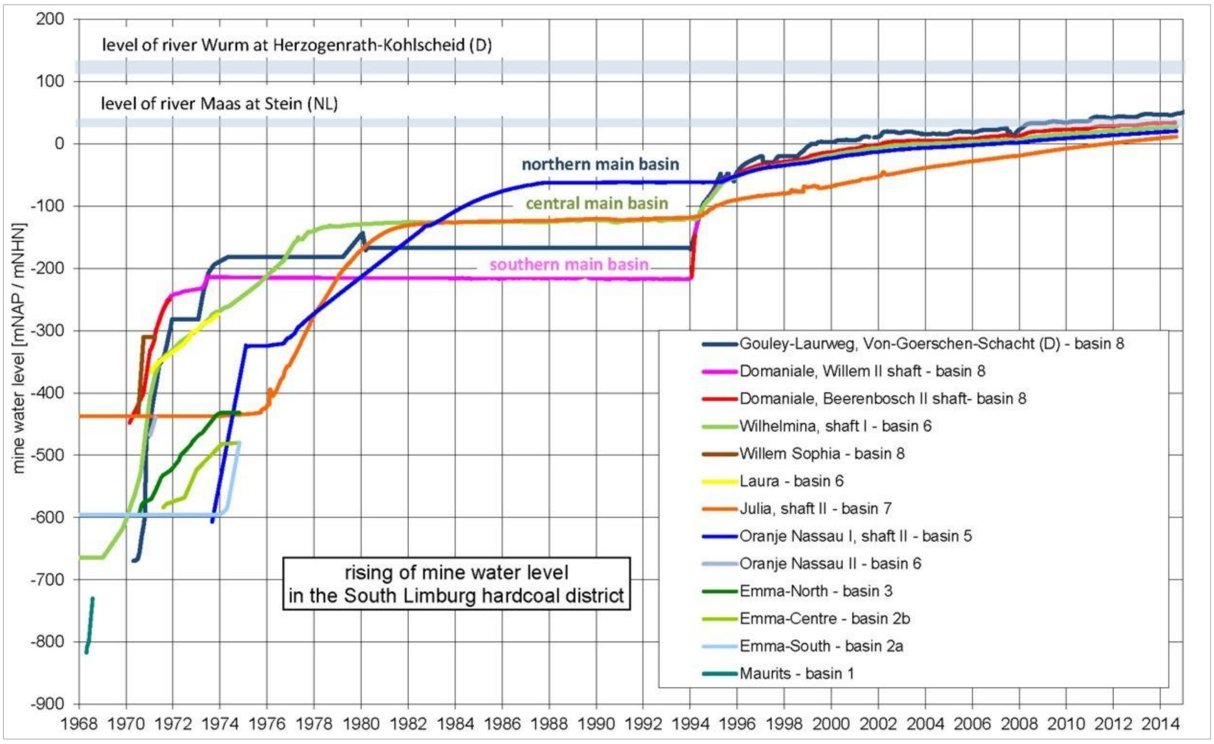


Fig. 21: Rising mine water levels in the South Limburg hard coal district

In these mines the mine water was kept at a low level until 1994 to protect the German mines east of the Feldbiß fault (“eastern mine water province”) from flooding.

Since November 1987, when the mine water level exceeded -63 mNAP in Emma and Hendrik mine, all Dutch mine water basins (besides Maurits (1) and Hendrik NE (4); Fig. 17) were hydraulically connected.

In this period three main basins developed with different mine water levels according to the level of the respective connecting gallery to the pumping station in Domaniale:

- a northern main basin with a hydraulic head at -63 mNAP (Emma, Hendrik, Oranje Nassau I, III, IV)
- a central main basin with a hydraulic head at about -120 mNAP (Oranje Nassau II, Wilhelmina, Laura)
- a southern main basin with a hydraulic head at -214 mNAP (-167 mNAP in Gouley-Laurweg) (Willem, Domaniale, Gouley-Laurweg).

The galleries from Laura to Julia were closed by dams; nevertheless there is a significant hydraulic connection between these two mines due to water creeping around the dams. The mine water level in Julia corresponds to the level in Laura at a somewhat deeper level.

In January 1994 this protective pumping of mine water in Domaniale and Gouley-Laurweg (D) ended. Since then the mine water level rises in the whole region.

The pumping equipment in the Von-Goerschen-Schacht (Gouley-Laurweg, D) was preserved, which allowed for future regulation of the mine water levels.

The pumping station in Von-Goerschen-Schacht was used for a number of pumping tests during the rising phase to investigate the hydraulic connections in the subsurface between the individual mines. It was shown that there is a high hydraulic conductivity between the different mining zones and that the inflow from the southeast can be assumed to about 6,5 m^3/min in 2007 at a mine water level of about 25 mNAP in Gouley-Laurweg (ROSNER, 2011).

The rise of mine water can be observed in six shafts: Von-Goerschen-Schacht (Gouley-Laurweg, D), the Beerenbosch II and Willem II shafts (Domaniale), shaft I Wilhelmina, shaft II Julia, and shaft II Oranje Nassau I (Fig. 20, Fig. 21). When the mining activities were brought to an end the other shafts were filled up. In the five remaining shafts in South Limburg measuring devices were installed to monitor the mine water levels.

Five additional deep monitoring wells in the basement (HH1, HH2, HLN1, HLN2, HLN3) were installed during the mine water project in Heerlen. For these wells only selected measurements are available from 2007, 2008 and 2014. The heads measured in these wells show more or less the same levels as the measurements in shaft II, Oranje Nassau I, with additional influences from the local pumping for the mine water project.

Fig. 21 shows that mine water rise was more or less uniform in the whole western mine water province after the mine water levels in the three main basins reached a more or less uniform level in 1995. The speed of the rise of mine water is determined by the volume (mine workings, pore and joint volume) and by the flow (groundwater recharge) from Germany.

Surface outflows from the Dutch mines do not occur yet. Until December 2014 the mine water reaches a level between about 50 mNAP in Gouley-Laurweg and about 21 mNAP in Oranje Nassau I; Julia still is at a slightly deeper level of about 11 mNAP. The average speed of the mine water rise from the year 2003 on is about 2,5 m/a, respective about 4,9 m/a for Julia.

3.8 Present mine water flow system

The present mine water flow system is schematically shown in Fig. 22. The inflow towards the mines decreased from 48 m^3/min (operation period) to about 6,5 m^3/min in 2007. ROSNER (2011) calculated this by analysing pumping tests performed in the Von-Goerschen-Schacht and the rise of mine water levels over certain time periods. For the final state, when the mine water level might reach the level of the Wurm river valley ROSNER (2011) assumed a total inflow of about 3 to 4 m^3/min. This inflow from the southeast was used to calibrate the groundwater model.

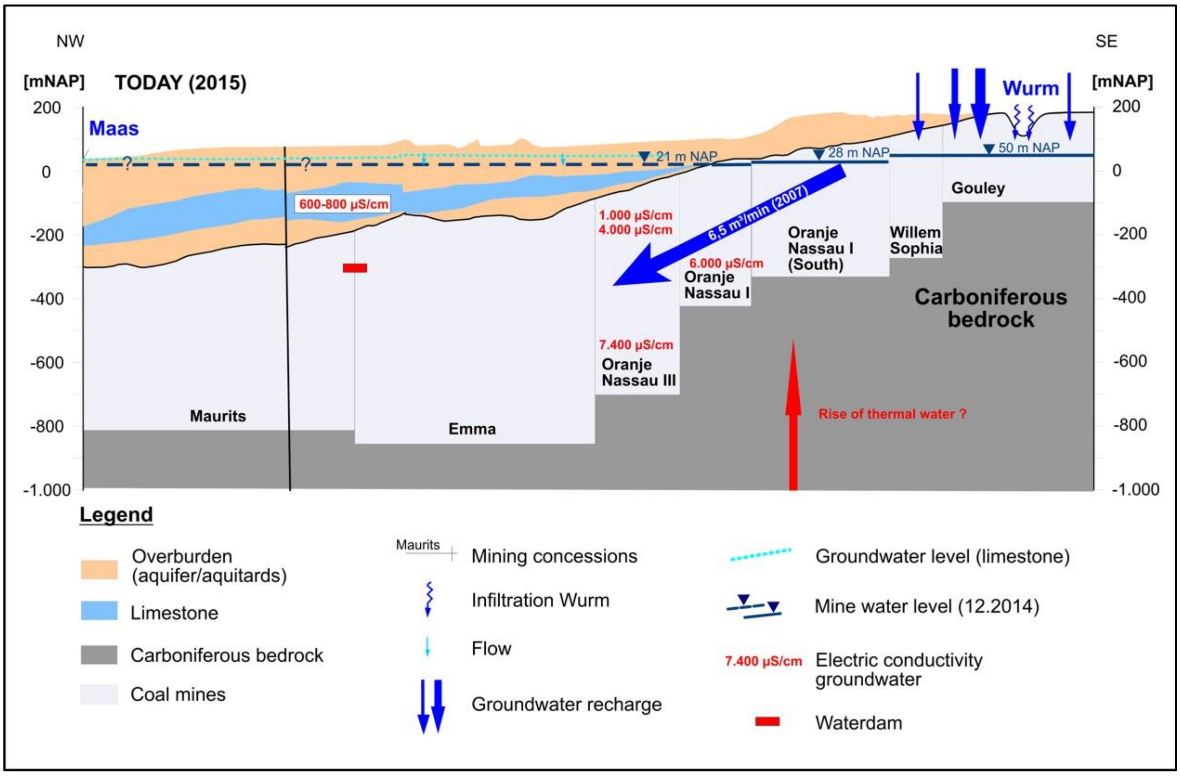


Fig. 22: Ground-/mine water inflow and average ground-/mine water quality today (shown schematically)

The amount of ascending thermal water is not known. Due to the sealing of the outflow paths and the higher water levels in the mines the amount of rising thermal water should now be much lower than in the period of active mining.

After the pumping of mine water stopped, an equilibrium was formed between fresh and salt water at the base of the overburden/top of basement. The electric conductivity is here about 1.000 µS/cm (based on measurements in the deep monitoring wells from the Mine water Project in Heerlen). During a pumping test it rose to 4.000 µS/cm after 20 days, which indicates that the mineralisation in the deeper parts of the basement is still high (ROSNER, 2011).

In the mining concessions such as Oranje Nassau I North, where the mine water level in 2015 had not yet reached the top of the basement the electric conductivity is higher (approximately 6.000 µS/cm)[1]. It shows that there still is an influence from the inflow of thermal water.

The following conclusions, derived from the analysis of the groundwater flow system in the basement, were used to construct the groundwater model:

- The general flow direction was and still is from the Wurm Valley towards the river Maas. The total flux dropped to 5 to 10 % relative to the flux at the operational time of the mines and is expected to drop further in the future.
- The unmined basement between Emma and Maurits is a major flow barrier at which significant drops of the hydraulic heads are expected. Due to the lack of monitoring wells, the real groundwater levels cannot be measured.
- The hydraulic connections between the basement and the overburden can be identified only on a regional level (concessions). There is a trend showing a higher recharge in the southeast due to a thinner or missing overburden.
- In 2015 there is still a downward flow from the upper aquifer towards the basement.
- There are strong indications that the deep saline groundwater is stratified.

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[1] Sea water with approximately 30 g/l NaCl has an electric conductivity of approximately 50.000 µS/cm.

4 Hydrogeological system of the overburden

4.1 Hydrogeological structure of the overburden

The hydrogeological system of the overburden is characterised by a complex layering of several aquifers and aquitards from the Cretaceous to the Quaternary formations.

The layers are slope downwards towards the northwest as shown in Fig. 23. Therefore the thickness increases from the southeast towards the Northwest near the Maas (approximately 400 m). In the southeast - near the Wurm - the overburden is very thin or missing in an area of approximately 14 km^2 and the basement locally crops out.

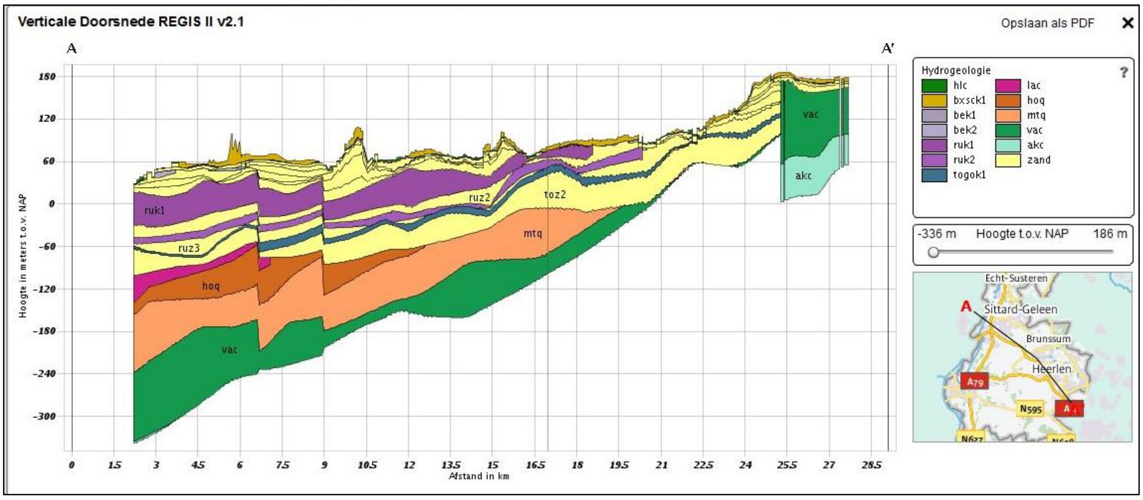

Fig. 23: Geological structure of the overburden according to REGIS-II v2.1

In the following chapters, the overburden is described starting with the oldest Cretaceous layers, which lie directly on top of the Carboniferous, and end with the youngest Quaternary deposits.

4.1.1 Aachen and Vaals formation

The oldest geologic formation is the Aachen formation. This formation is present at only a few locations south of the Heerlerheide fault. It consists of a layer of fine sands with a thickness between 20 to 50 metres. These sands often contain heavy clays with lignite and pyrite. In Fig. 24 the presence and thickness of the Aachen formation (according to REGIS-II v2.1.) is shown.

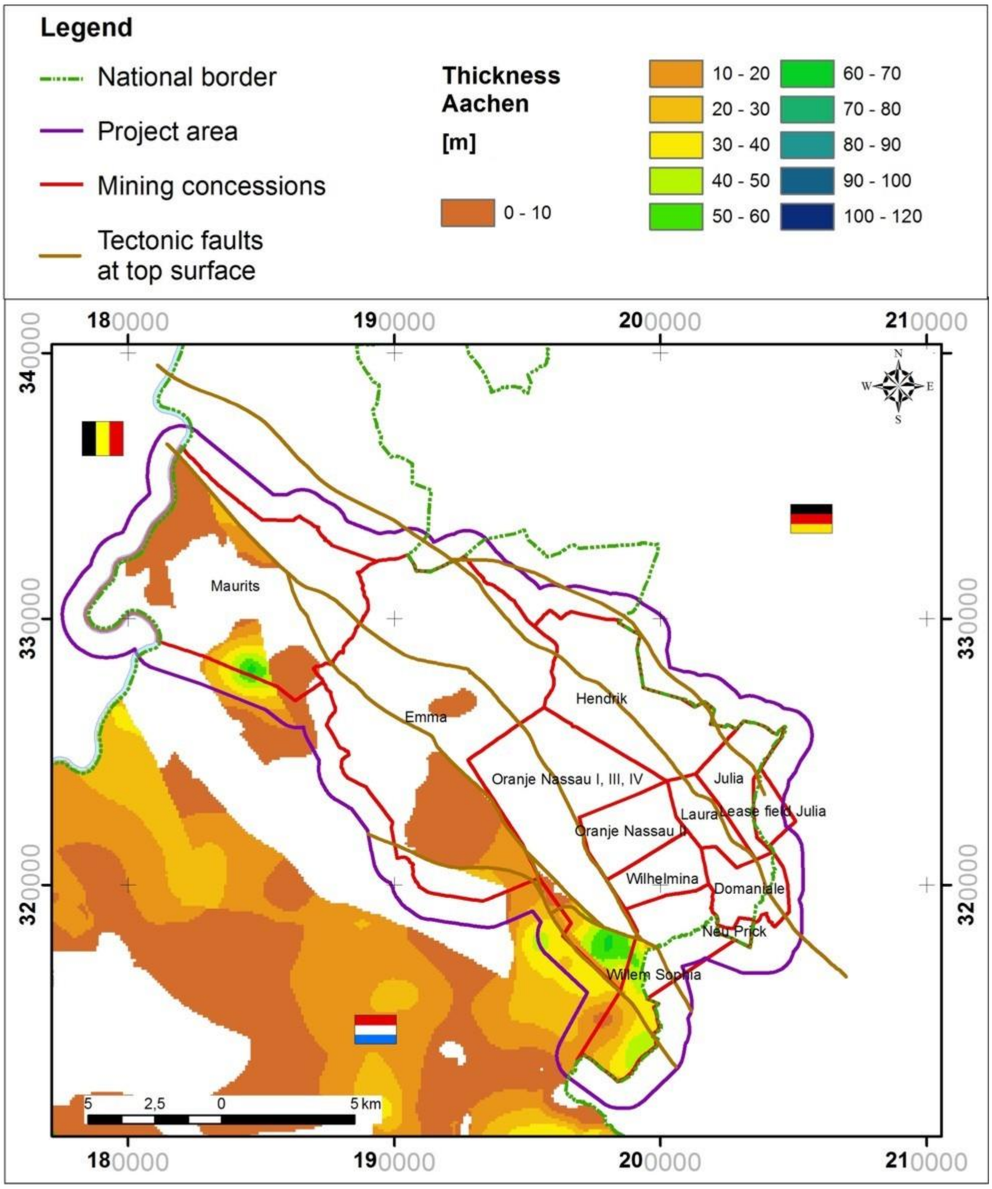

Fig. 24: Aachen formation: thickness and presence (REGIS-II v2.1)

On top of the Aachen formation lies the Vaals formation. This layer is present almost everywhere south of the Heerlerheide fault (Fig. 25).

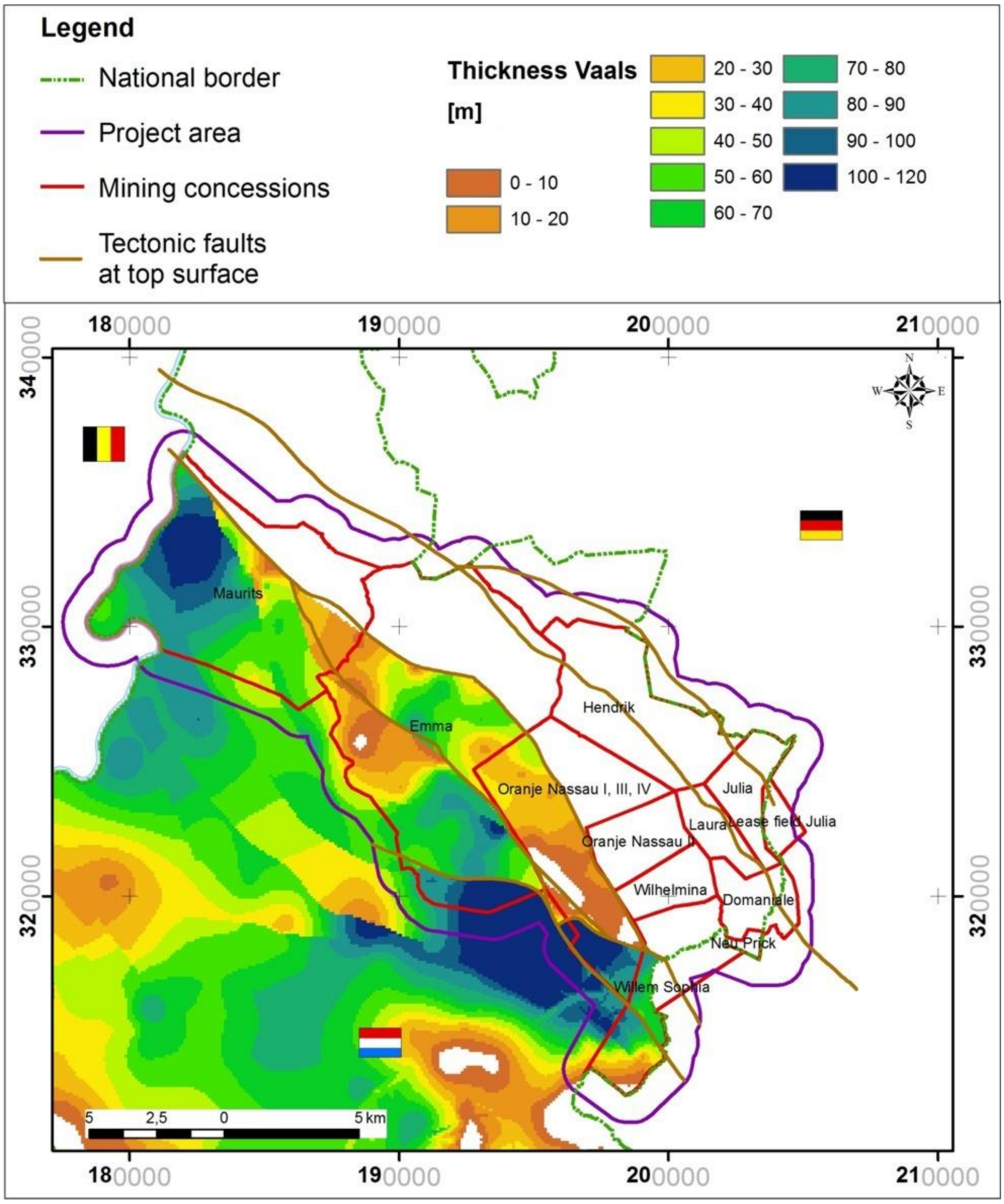

Fig. 25: Vaals formation: Thickness and presence (REGIS-II v2.1)

On a few locations, where the sandy part is higher, groundwater extraction from this layer is possible, for example in the southeast corner of the Oranje Nassau I, III, IV concession. The thickness of the layer fluctuates strongly between 50 and 100 m.

4.1.2 Maastricht/Houthem formation

Next in line are the chalk deposits from the Cretaceous (Fig. 26). They consist of the Gulpen, Maastricht, and Houthem formations. The Gulpen formation is not present in the project area.

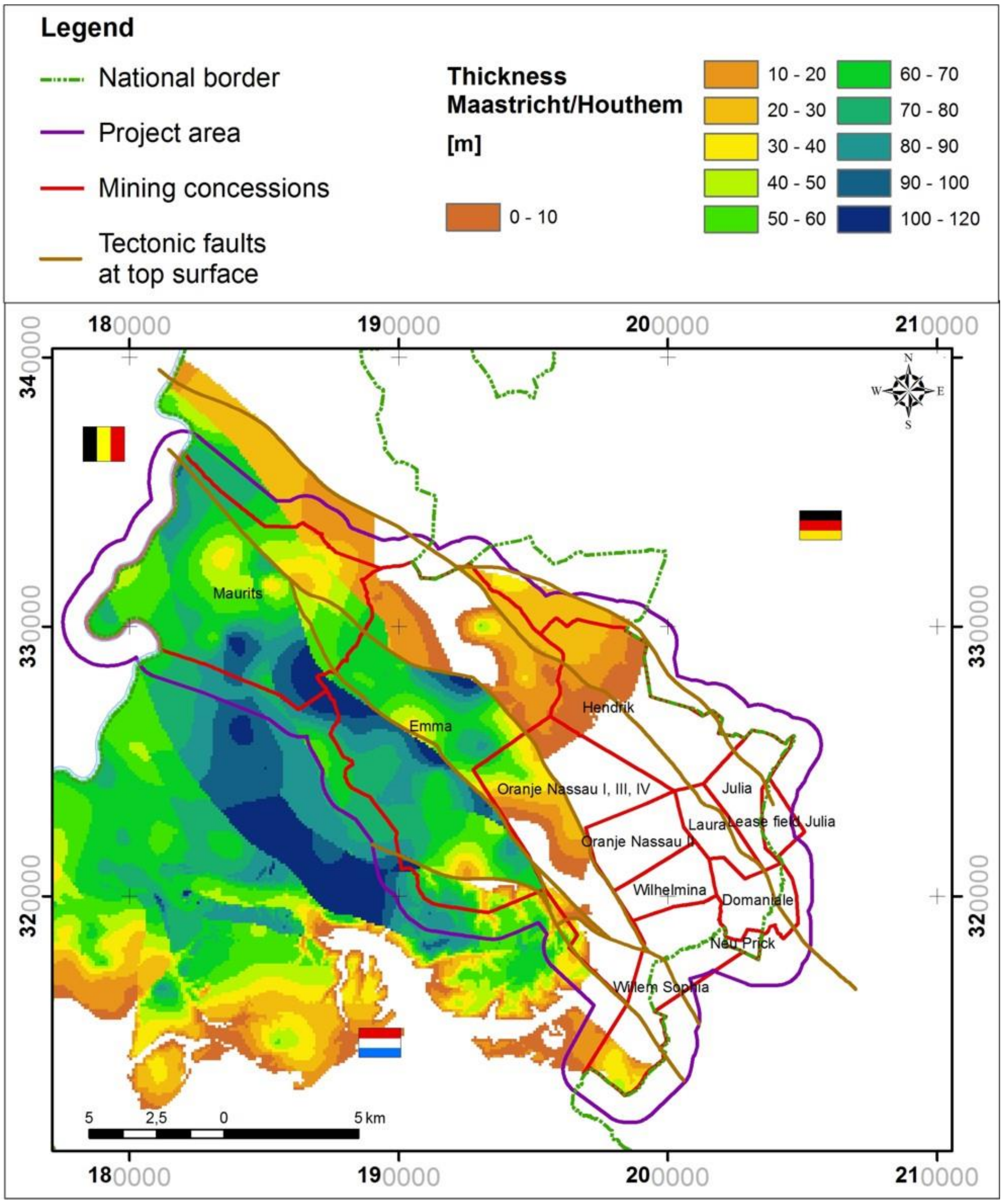

Fig. 26: Maastricht Houthem formation: Thickness and presence (REGIS-II v2.1)

The upper parts of the chalk formations are weathered as a result of their karstic characteristics. Therefore, the Maastricht and Houthem formations are the main aquifers for the production of drinking water companies and the extraction of groundwater by industries. These formations consist of chalk deposits with a thickness between 30 and 90 m (Maastricht) and 20 to 40 m (Houthem).

South of the Heerlerheide fault both layers are present. The Houthem formation only exists in the northwest part of the project area. North of the Heerlerheide fault (in the SE part of the investigation area) the Maastricht formation locally lies directly on top of the Carboniferous.

4.1.3 Tongeren/Rupel and Breda formation

The Tongeren formation is younger than the chalk deposits and is present over a large area; the Tongeren formation (Fig. 27) consists of clay and sand. North of the Heerlerheide fault it lies partly direct on top of the Carboniferous. The lowest parts of this formation contain clay layers which cause the overall layer to be characterised by a low permeability.

The youngest deposits are the Rupel formation (clayey sands and clays) and the layers that form the upper aquifer, known as the Breda formation. Maas deposits contain gravel, sand and clay. The top layer, deposited in the Quaternary, consists of silty sediments (Löss).

4.2 Discussion differences REGIS-II v2.1 and REGIS-II v2.2

Model calculations were performed using the groundwater model IBRAHYM version 2015. This model is based on the geohydrological schematisation of the subsurface in REGIS-II v2.1. During the period in which this research was done

TNO updated REGIS-II v2.1. In order to determine the relevance of this update for IBRAHYM and the modelling results an analysis was performed to determine where REGIS-II v2.2 differed from REGIS-II v2.1. Subsequently, it was determined whether IBRAHYM could still be used unchanged, or whether an update of the schematisation of the subsurface was required. A brief summary of the results is shown below. This summary is based on a more detailed analysis in (WITTEVEEN+BOS, 2015).

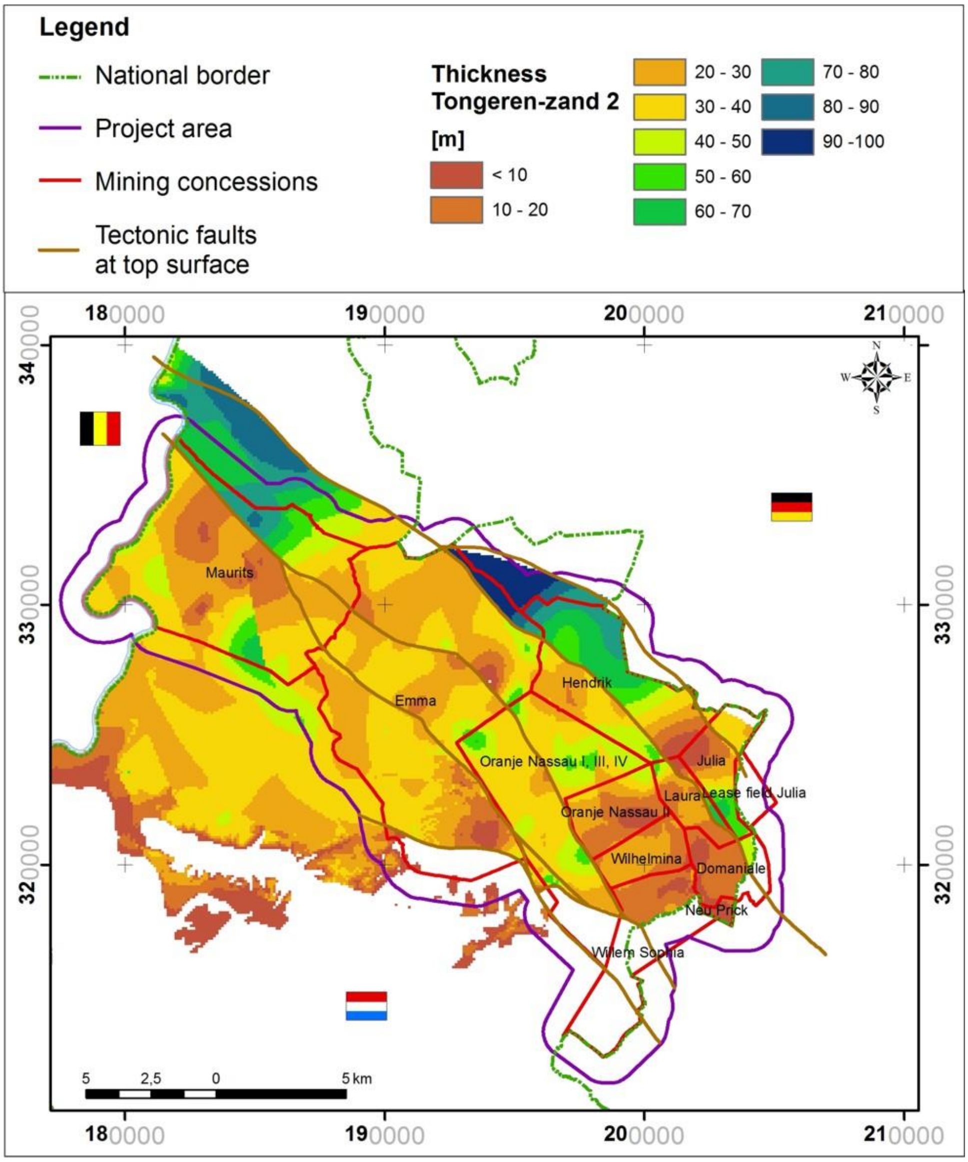

Fig. 27: Tongeren-Sands: Thickness and presence (REGIS-II v2.1)

For each of the geological formations shown in chap. 4.1, maps were created showing the difference in thickness between REGIS-II v2.1 and REGIS-II v2.2. In total, about 20 locations were identified where significant differences were found. For each of these points the cause of the difference was determined and what the consequences were for the modelling process. This analysis was partly based on input by TNO 2015.

The analysis shows that the biggest differences were caused by a new interpretation of drilling data. Samples that were initially classified as limestone belonging to the Maastricht formation were now classified as belonging to the Houthem formation. Additionally, the thickness of several layers was adjusted according to new data.

In WITTEVEEN+BOS (2015) a detailed analysis is provided on the differences between the two REGIS models. For now, it suffices to conclude that there are differences, but these differences occur locally, at the edges of the research area, or near faults, where the elevations at which geological layers are found already show large variations over short distances. The quantification and visualisation of the differences was deemed to be an important step considering future updates for the models. It was also concluded that it was not necessary to update IBRAHYM before performing the calculations. The current version of IBRAHYM was deemed sufficiently accurate as a regional groundwater model for this research.

4.3 Groundwater levels in the overburden

4.3.1 Phreatic groundwater and 1st aquifer

The IBRAHYM model is used to perform steady-state and transient calculations of the groundwater level in the research area. Fig. 28 shows the calculated phreatic groundwater level.

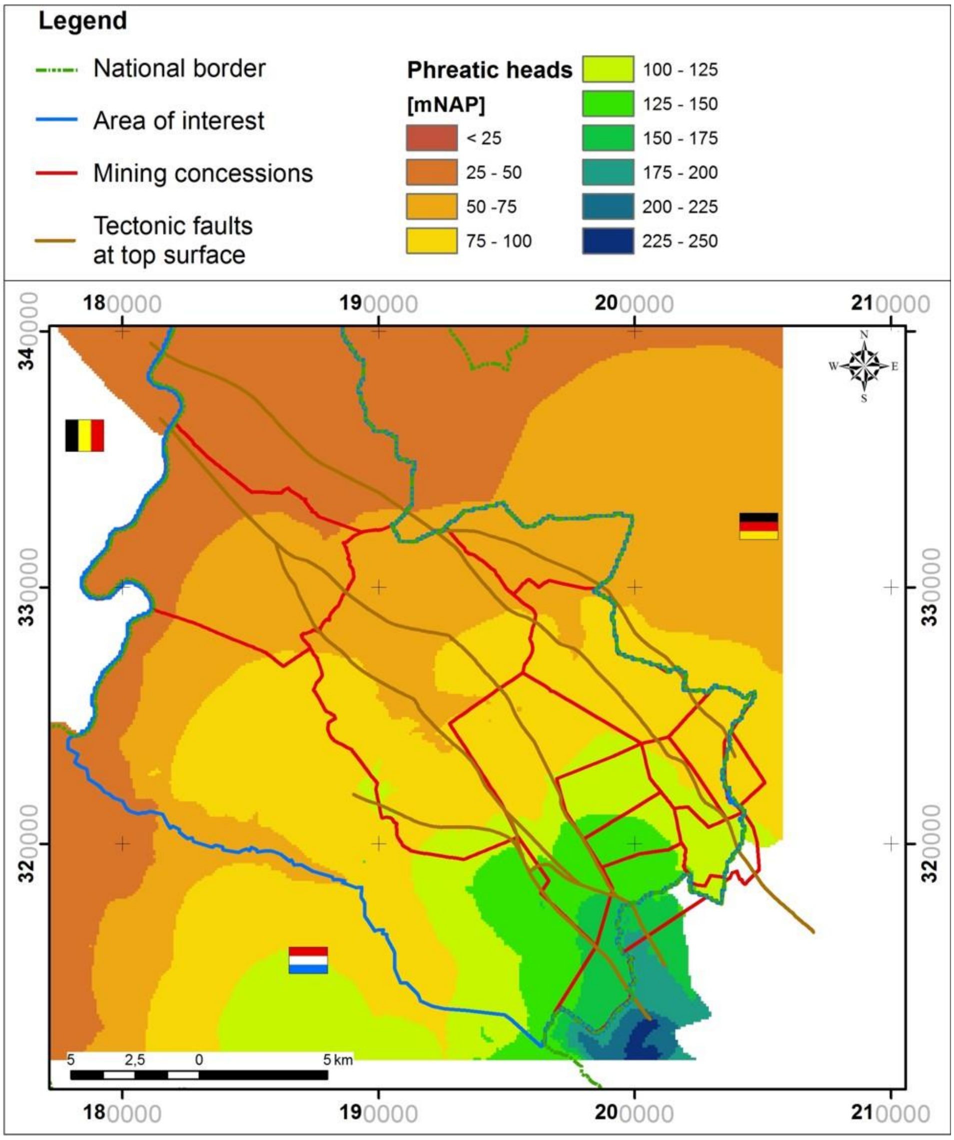

Fig. 28: Phreatic heads in the IBRAHYM model

The inset shows a zoomed portion of the map, in which the more elevated regions in Heerlen/Kerkrade can be identified. This region is also known as the plateau of Schimmert and is characterised by a radial flow of groundwater towards the surrounding stream valleys. The low groundwater levels near the Maas (at around 40 mNAP) can also be identified.

4.3.2 Second aquifer

The Maastricht and Houthem formations are often referred to as the second aquifer within the investigation area. There are only few available groundwater monitoring wells. In the 1980s four monitoring wells were installed to measure the effects of rising mine water. The filters were installed in the overburden directly above the basement with several filter sections to monitor the possible effects of rising mine water.

The location of groundwater monitoring wells is shown in Fig. 29:

Stein	B60C0860 (4 Filters), Maurits concession;
Schinnen	B60C0839 (3 Filters), Emma concession;
Hoensbroek	B62B0837 (4 Filters), Emma concession;
Voerendaal	B62B0838 (4 Filters), Emma concession.

4.3.3 Development of groundwater levels

Generally, the groundwater heads in the deep aquifer are influenced by several factors including long-term fluctuations, deep groundwater extractions and the effect of rising mine water. In Fig. 30 to Fig. 33 the groundwater levels are shown in the four mine water monitoring wells. All of the wells show an increasing groundwater table in the second aquifer since the 1990s.

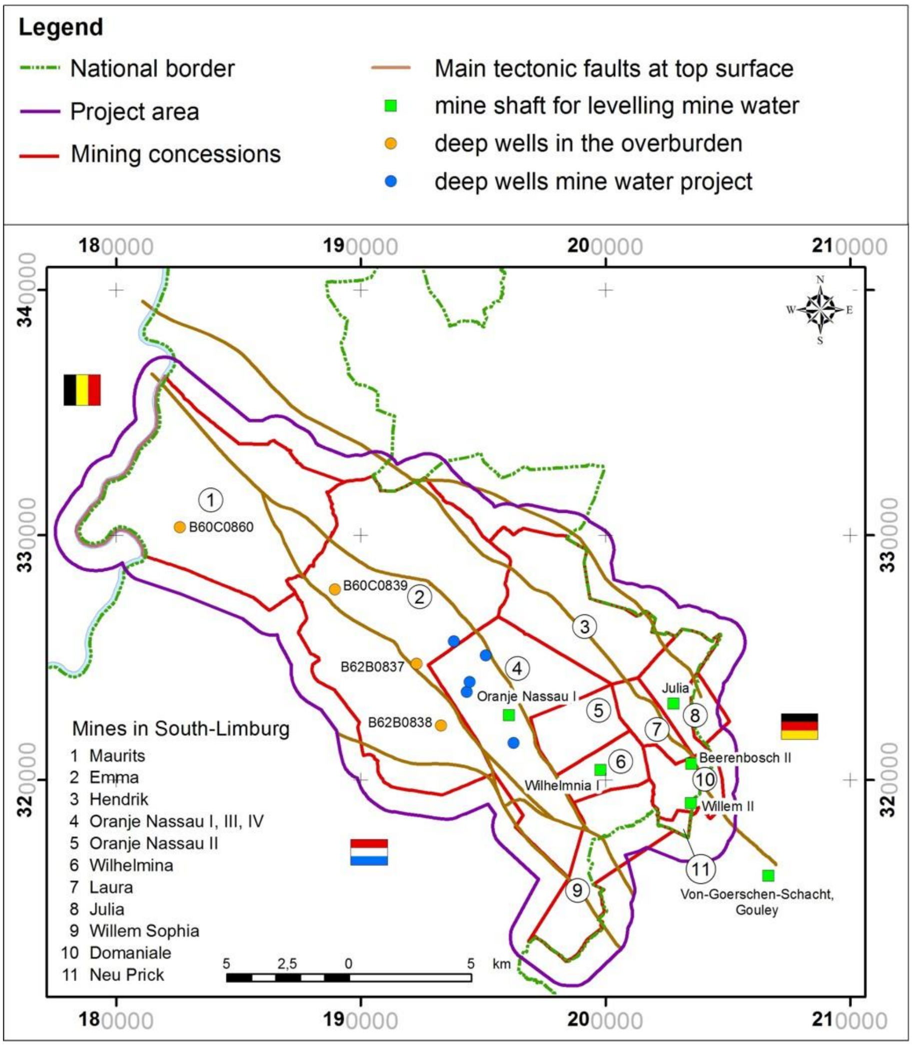

Fig. 29: Groundwater monitoring wells and former mine shafts used for monitoring the mine water level

The measurements in monitoring well B60C0860 (Stein) show the most significant reactions on rising mine water:

- No significant change in shallow groundwater levels (filter 1)
- Rise of groundwater head in the second aquifer (Maastricht and Houthem formations) since the early nineties, with approximately 20 to 25 m;
- The parallel development of the groundwater levels in filters 3 and 4 indicates that there is a hydraulic connection between the different layers.
  In all layers a rise of the groundwater head is shown.

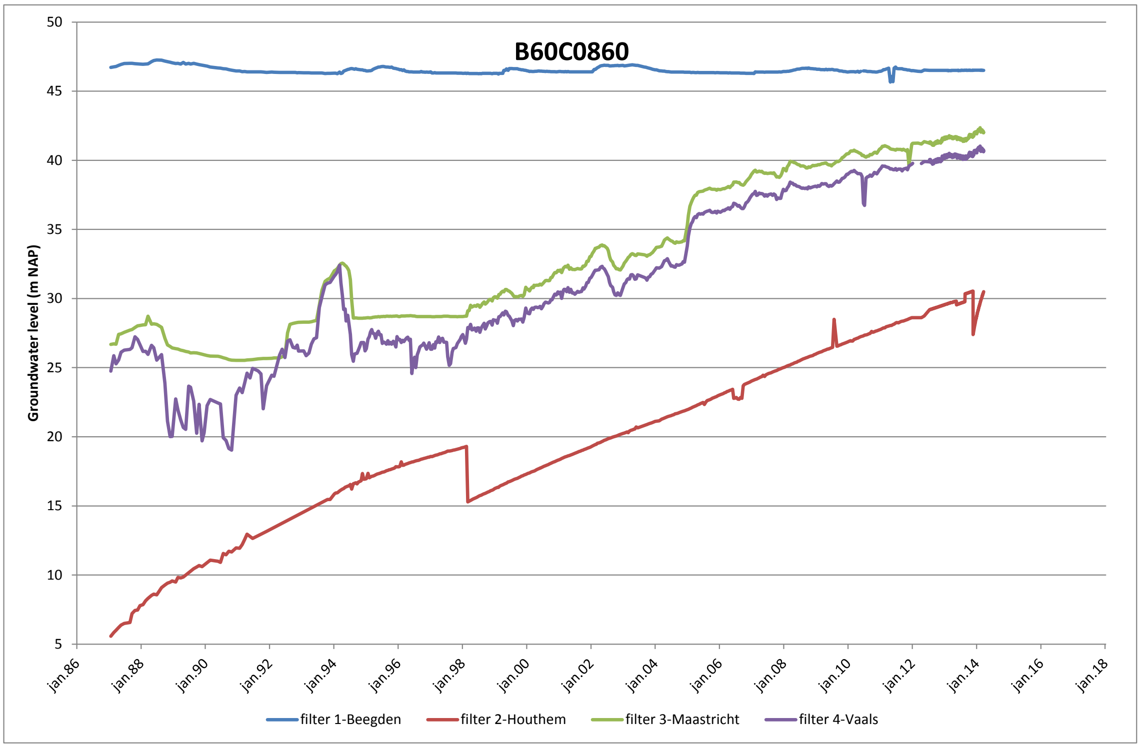

Fig. 30: Monitoring well B60C0860 (Maurits concession)

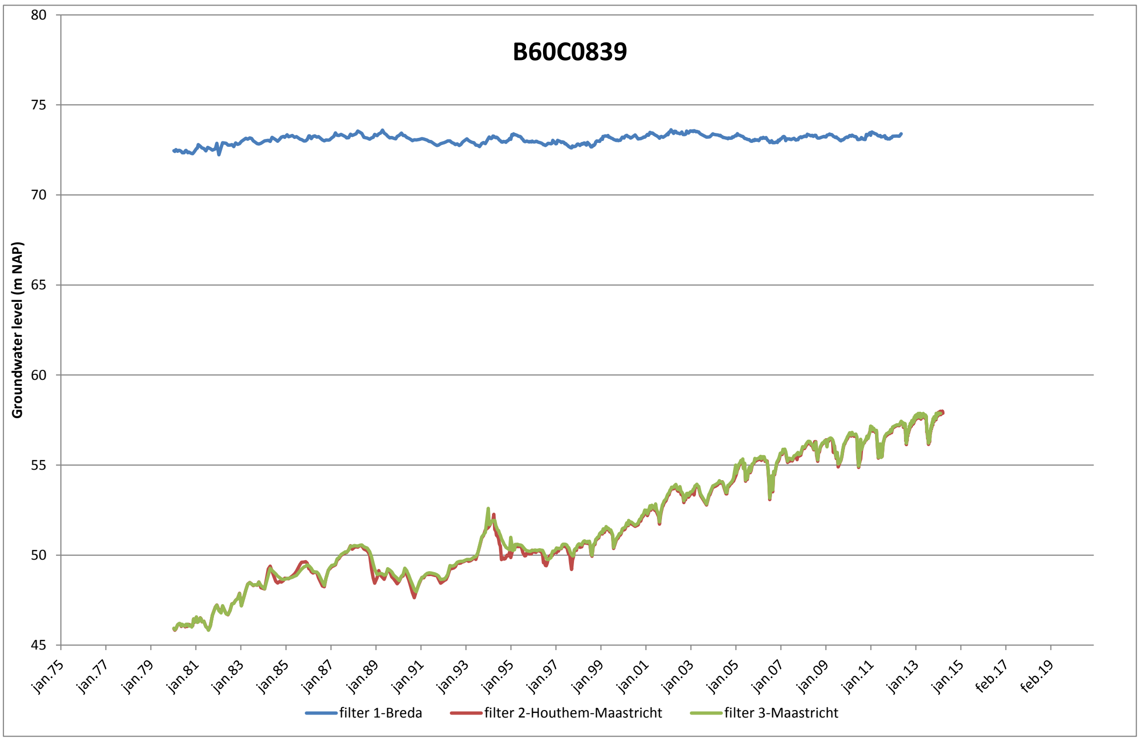

Fig. 31: Monitoring well B60C0839 (Emma concession)

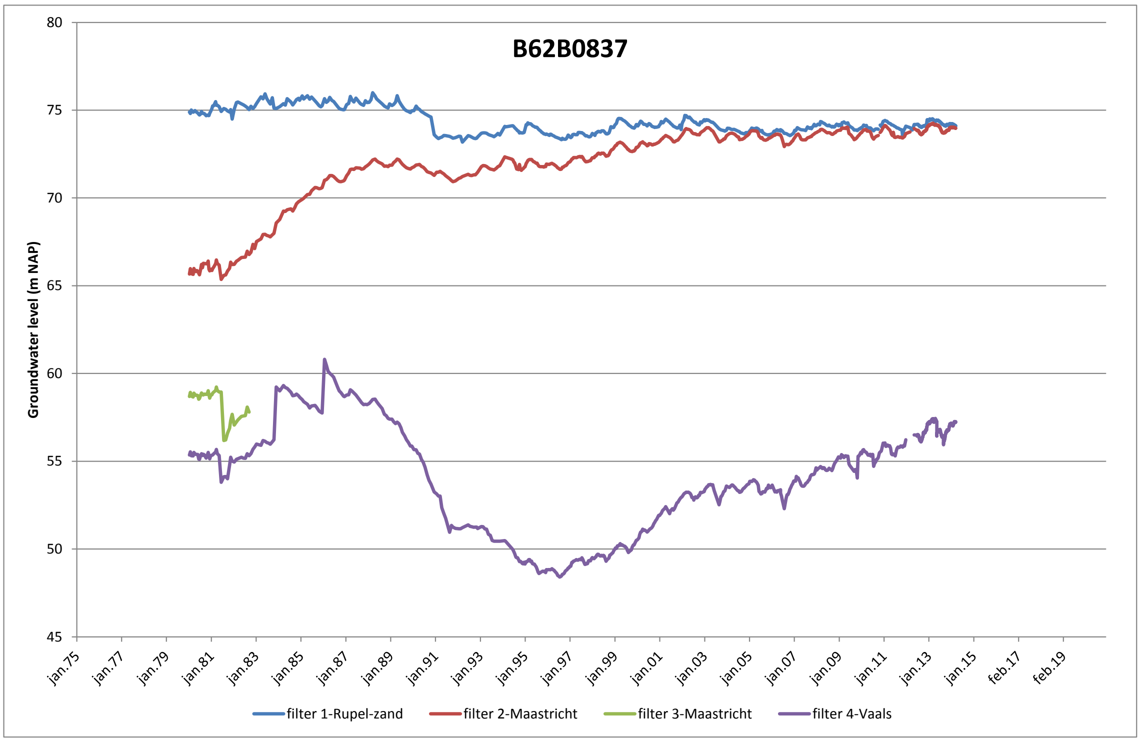

Fig. 32: Monitoring well B62B0837 near Hoensbroek (Emma concession)

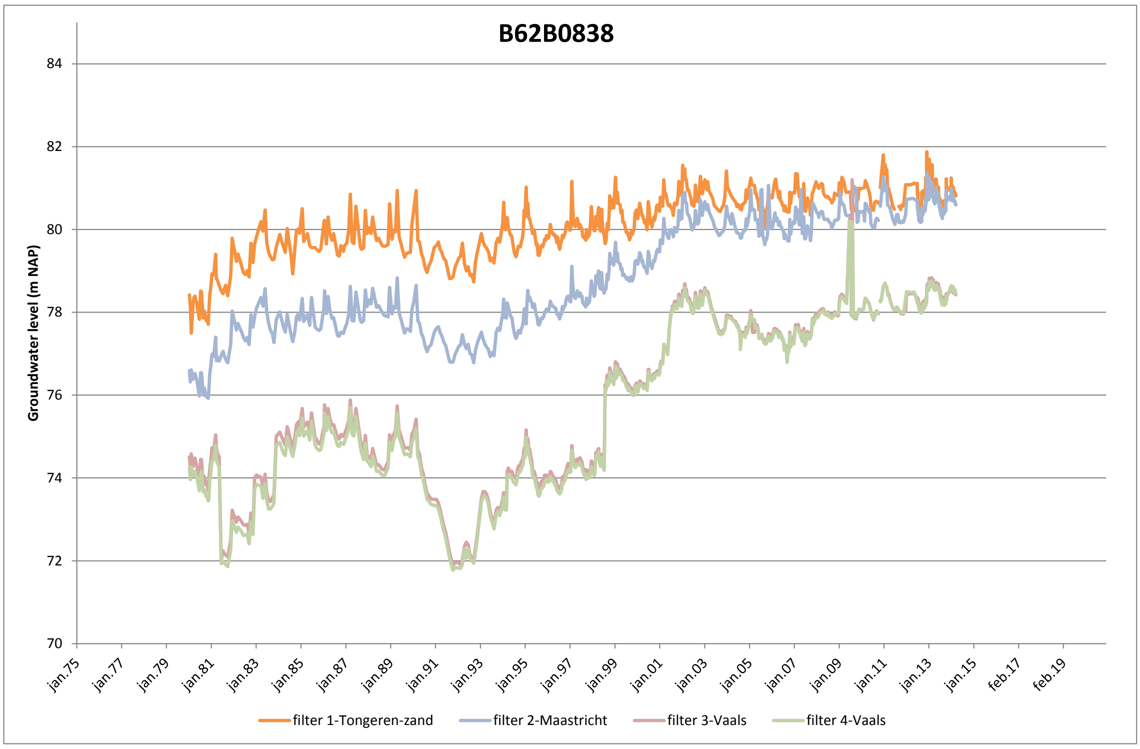

Fig. 33: Monitoring well B62B0838 near Voerendaal (Emma concession)

The observed increase in well B60C0839 (Schinnen) is from 46 mNAP to 58 mNAP over a period of more than 30 years. Measurements in filter 1 show a more or less continuous groundwater level.

Measuring point B62B0837 (Hoensbroek) shows a decreasing groundwater level from 1983 to approximately 1997 in the level of the Vaals formation followed by a continuous increase of the groundwater level until the present. Measurements from the deep filter in the Maastricht formation are only available at the beginning of the 1980s; the development of the heads with time seems to be correspondent to the situation in the Vaals formation.

The filter in the upper level of the Maastricht formation does not show the intermediate decrease of the piezometric heads in the 1990s. In this level two phases of constant increase of the groundwater level in the 1980s and in the 1990s with a short phase of decrease in 1989 to 1991 can be observed. In the beginning of the 2000s an equilibrium is reached with the groundwater level in the 1st aquifer. Since then groundwater level in the upper Maastricht formation is more or less constant depart from the seasonal influence from rainfall.

These measurements show the combined effect of rising mine water and a decreasing withdrawal of groundwater by the water company in Limburg, which shows the most influence in the deeper levels of the overburden.

The southeastern most located well B62B0838 (Voerendaal) shows a similar development of the groundwater levels as the well B62B0837 with less significant undulations.

In chap. 8 these measurements are discussed more in detail.

4.3.4 Groundwater extractions

The current locations of groundwater extractions are shown in Fig. 34. The colour of the dots indicates the stratigraphic level of the extraction.

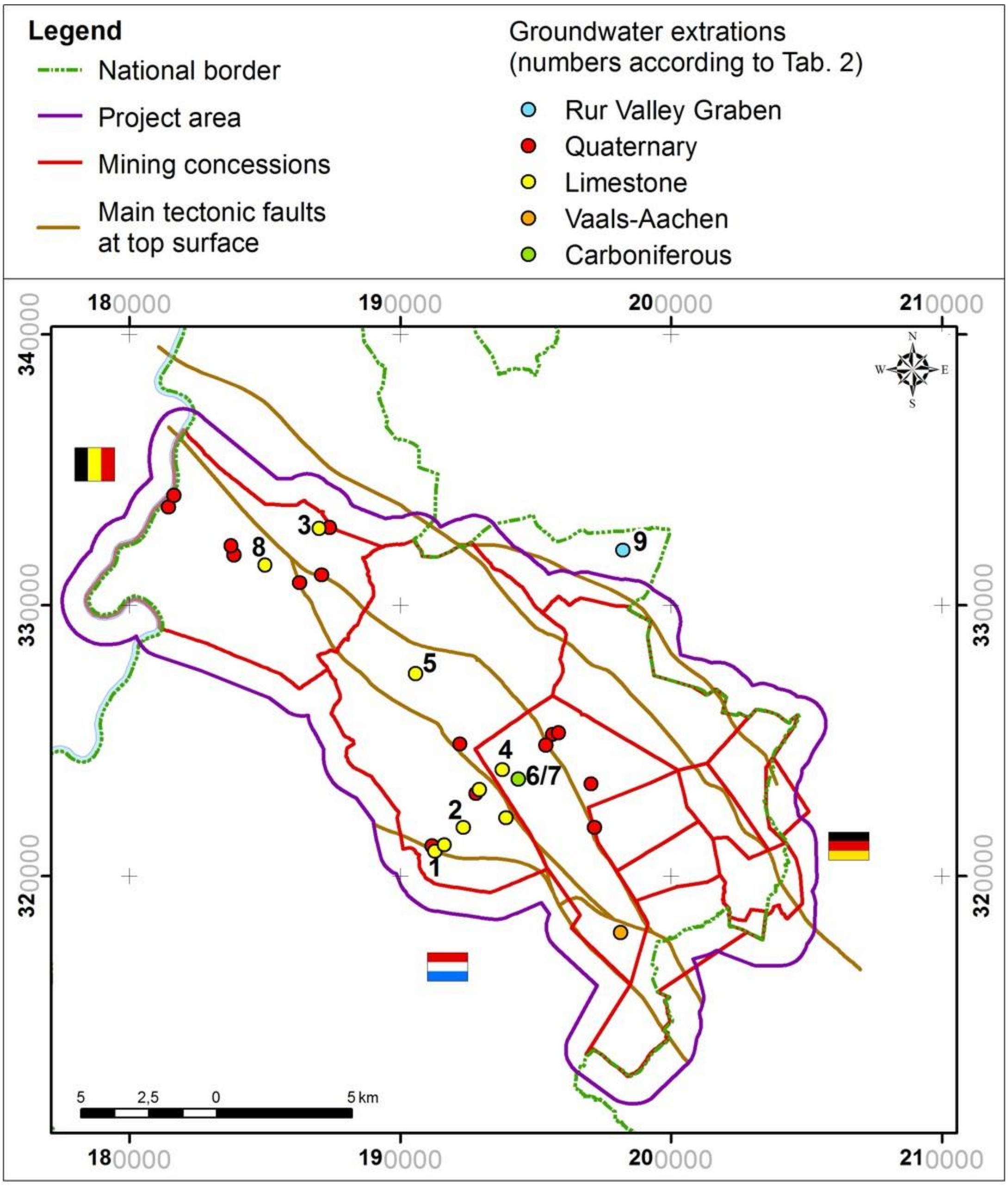

Fig. 34: Shallow and deep groundwater extractions

Tab. 2 summarises the relevant groundwater extractions in the main aquifer (Maastricht) and in the overburden.

Tab. 2: Groundwater extractions (for location see Fig. 34)

No.	Groundwater extraction	Aquifer	Depth [m below surface]	Purpose	Permit [m^3/a]
1	P.S. CRAUBEEK	Maastricht	55	Drinking water	3.500.000
2	HOENSHUIS GOLF	Maastricht	78	Irrigation	18.000
3	ZIEKENHUIS SITTARD-GELEEN	Maastricht	180	Thermal storage system	900.000
4	REFRESCO BENELUX BV LOCATIE HOENSBROEK	Maastricht	140	Process and product water for nutrition	600.000
5	ALFA BROUWERIJ	Maastricht	151	Process and product water for nutrition	200.000
6	PROEF KWO PARKEERTERREIN IKEA TERHOEVENERWEG HEERLERHEIDE	Carboniferous	700	Thermal storage system	2.200.000
7	TROMPENBURGSTRAAT TERHOEVENDERWEG	Carboniferous	230	Thermal storage system	499.900
8	DSM ONTTR MAASGRINDEN	Beegden	-	Process water	1.800.000
9	P.S. SCHINVELD	Rur valley graben	200	Drinking water	5.000.000

Most of these are situated in the upper aquifer (Quaternary deposits) and in the limestone. One extraction lies north of the Feldbiß fault and extracts groundwater from the Rur Valley Graben. All these extractions are points of interest with respect to the effects of mine water rise.

4.3.5 Development of groundwater quality

The influence of mine water on groundwater quality should be noticeable through a higher chloride and sulphate content of the groundwater. In the samples from the mine water project in Heerlen the chloride concentration reaches 6.000 mg/l sulphate, formed through the oxidation of pyrite (FeS_2), is also a typical indicator for mine water. Until now, there has been no mine water flow from the basement to the overlying aquifers in the overburden due to the higher potential in the overburden. Therefore, the chloride content in the overburden still is comparatively low (Tab. 3).

Tab. 3: Groundwater analysis in the “Zoutwachters”

Measuring point / Filter	[mg/l]	09.1979	12.1982	11.1983	01.1986	03.1998
B60C860 Stein / 3	Cl	-	3	2	<1	7
	SO_4	-	5	2	5	10
B60C860 Stein / 4	Cl	-	2	3	4	57
	SO_4	-	4	10	6	<0,4
B60C0839 Schinnen / 2	Cl	25	6	2	4	5
	SO_4	30	7	4	9	9
B60C0839 Schinnen / 3	Cl	7	8	5	6	6
	SO_4	10	9	6	12	10
B62B0837 Hoensbroek / 4	Cl	17	17	15	14	11
	SO_4	39	44	58	52	35
B62B838 Voerendaal/ 3	Cl	12	15	18	15	19
	SO_4	34	54	48	55	61

5 Hypothesis

5.1 Groundwater flow 2015

The current knowledge about the groundwater flow system - before groundwater modelling was performed - is presented in Fig. 35. This is a transient situation as the mine water levels are still rising. The characteristics of the actual flow regime can be described as follows (Fig. 35):

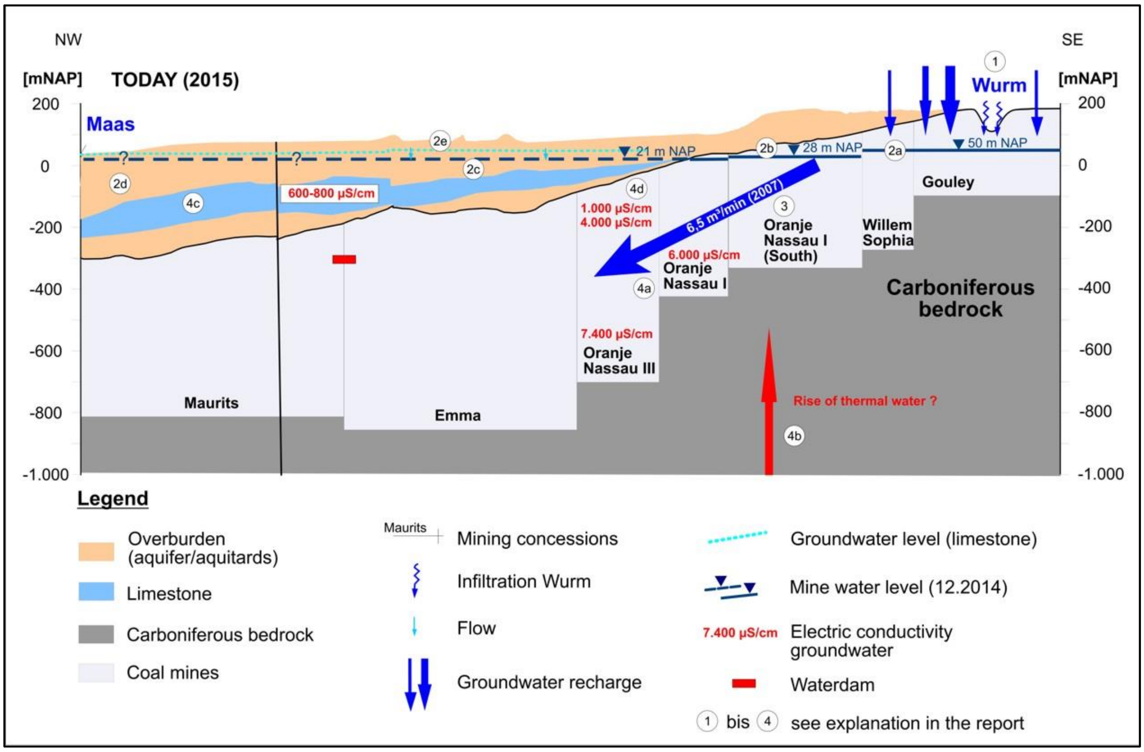

Fig. 35: Schematic representation of the current status of the ground-/mine water flow system

(1) The highest groundwater recharge occurs in the area where the overburden is missing (14 km^2), 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 approximately 6,5 m^3/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 m^3/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 µS/cm.

(4d) The mine water near the top of the Carboniferous has an electric conductivity of about 1.000 µS/cm.

5.2 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. 36).

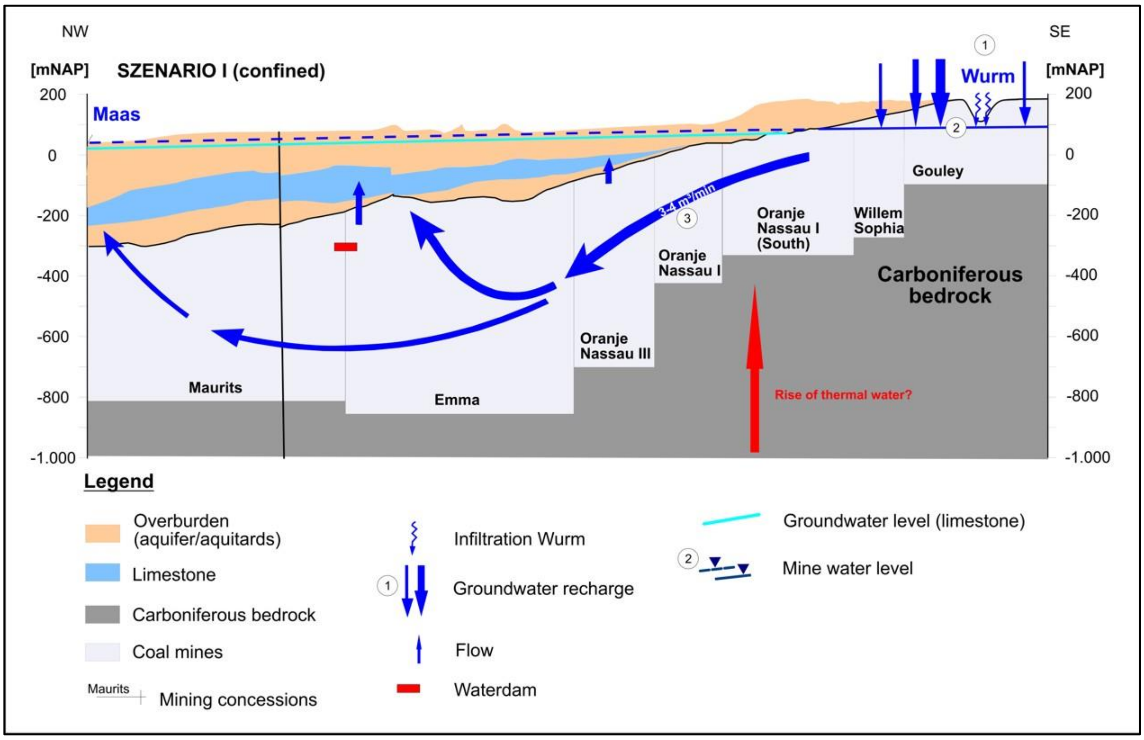

Fig. 36: Schematic representation of the hypothetical final situation of the confined ground-/mine water flow system (average case)

The main recharge is delivered from the southeast (Wurm river valley); the recharge rate is assumed to be 3 to 4 m³/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.

5.3 Land use and protection of drinking water extractions

Areas with high groundwater levels are the most vulnerable to the rise of mine water because of the risk of wetting. Fig. 37 shows the areas where groundwater is found less than 3,5 m below the surface level. 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.

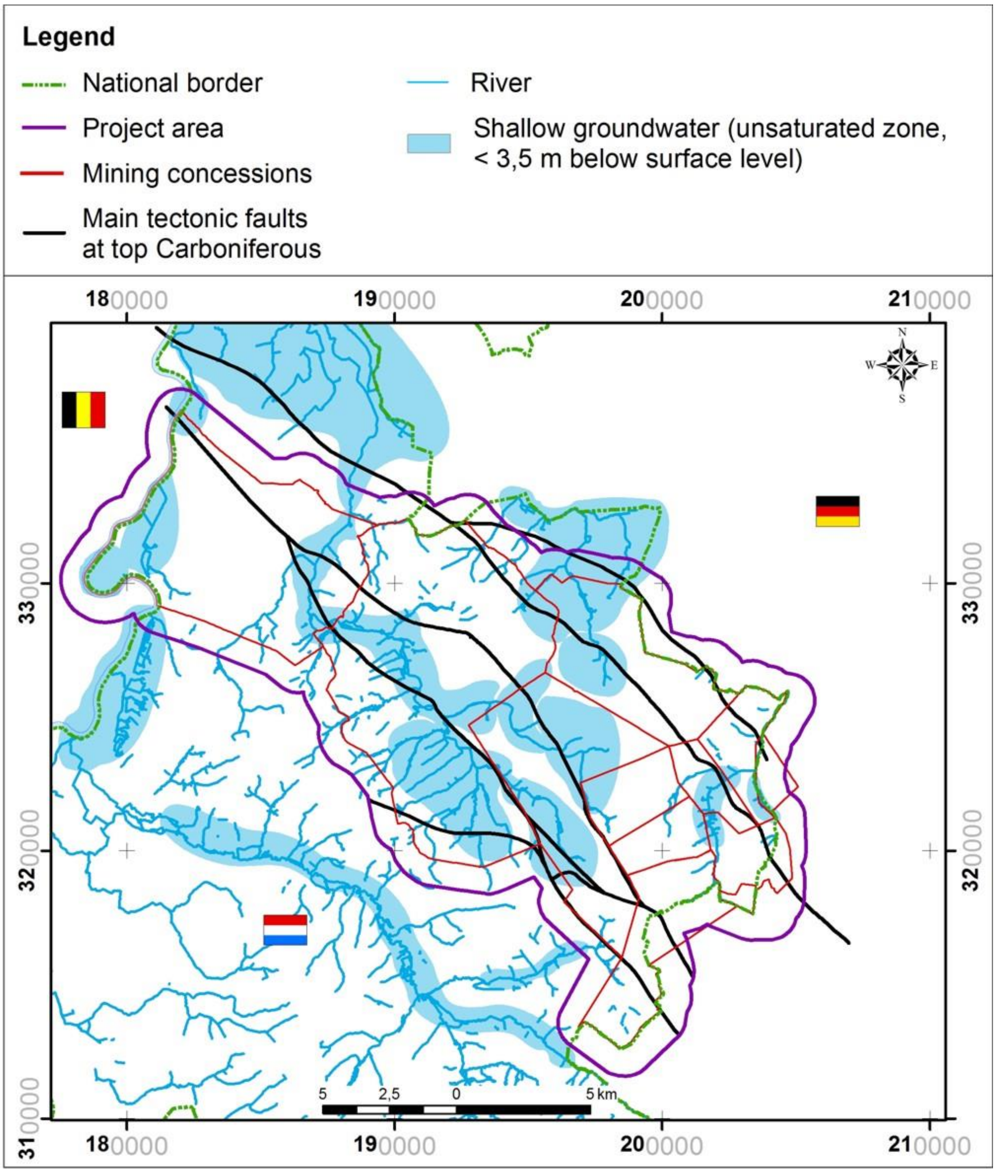

Fig. 37: Areas with thickness of the unsaturated zone < 3,5 m

A large part of the area of interest has a groundwater table deeper than 3,5 m below the surface level (white colour). This is caused by the high surface levels of the different plateaus in South Limburg. 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 area of interest).

Some smaller river valleys (Rode Beek and Anselderbeek) are also areas with a thinner unsaturated zone. A large area with high groundwater tables lies north of the area of interest. This area has a lower surface level due to erosion by the river Maas. Therefore, groundwater tables are higher there.

5.3.1 Land use

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. Some main roads are also situated in zones with a high groundwater table, especially in the north of the area of interest and parallel to the valley of the Geleenbeek.

5.3.2 Nature

The Province of Limburg has defined several types of nature reserves. These nature reserves are often situated in the river valleys which means they are often located in areas with a higher groundwater table. Areas with both a high groundwater table and an area of high natural value are therefore areas of interest regarding groundwater quantity. These areas are (Fig. 38):

- Valley of the river Maas;
- Valley of the river Geleenbeek and tributaries;
- Valley of the river Anselderbeek;
- Nature reserve Brunssummerheide;
- Valley of the river Rode Beek;
- Several forested areas in the north of the area of interest and near Schinveld.

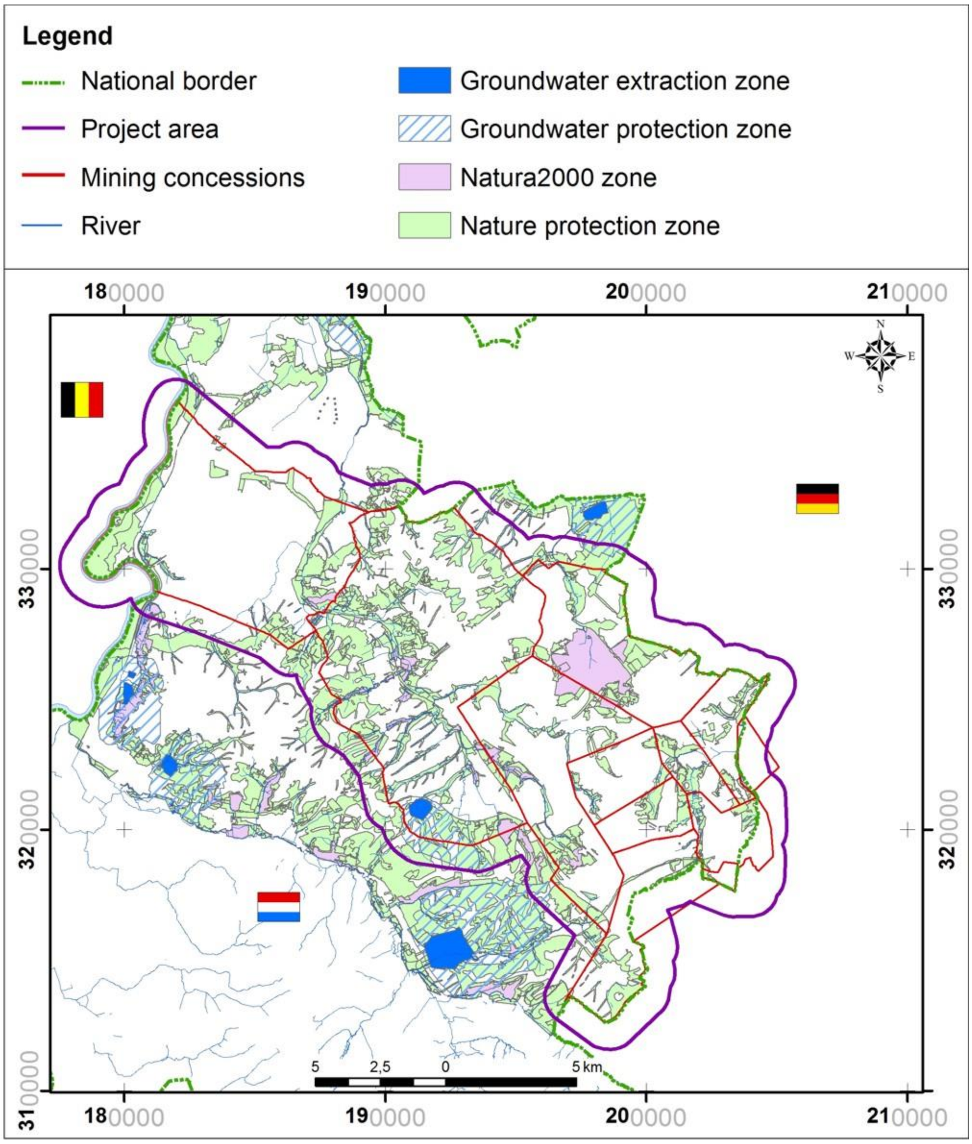

Fig. 38: Location of nature reserves with high groundwater level and groundwater protection zones

5.3.3 Protection zones drinking water and industrial extractions

In the investigation area the drinking water extraction Craubeek is protected by a “groundwater protection zone” (Fig. 38). Craubeek is situated in the Emma concession (extraction on both sides of the Kunrader fault).

In the research area there are two (deep) industrial groundwater extractions, both situated in the area of the Emma concession. Vulnerable industrial and drinking water extractions are protected against potential pollution by the Water Framework Directive and the Groundwater Directive.

In the “gebiedsdossiers” a number of measures are listed for the protection of the groundwater extractions. These measures range from monitoring to the implementation of controlling measures, etc. It must be noted that the industrial pumping wells are not regionally protected. Contrary to the approach for drinking water extractions, no protection zones or well capture zones are defined.

6 Groundwater model

6.1 Description

The groundwater model IBRAHYM is a regional hydrological model. It describes the groundwater system of the Province of Limburg. It has been developed by TNO/Deltares, Alterra, and Royal Haskoning.

The construction of the model was commissioned by the Waterboards Peel en Maasvallei and Roer en Overmaas, the Province of Limburg and the drinking water company WML. In 2015, Deltares updated the model by adding the area of South Limburg to the model and recalibrating it.

6.2 Model structure

The layers in IBRAHYM are based on REGIS-II v2.1 (Fig. 39). As mentioned before in chap. 3, REGIS-II v2.1 contains all geological formations between the surface and the Top Carboniferous.

The REGIS layers have been converted into 19 model layers. In Fig. 41 an example is given for how the REGIS layers are divided into the model layers. The IBRAHYM model contains the geological formations from Holocene to the Aachen formation.

Tab. 4 contains an overview of the geological formations and their corresponding model layers in IBRAHYM. Within the systematic of the IBRAHIM model it has to be regarded, that the numbers of the layers are different for each main hydrogeological unit/tectonic block (Hydrogeological homogeneous areas in Fig. 5). Therefore the same stratigraphic layer may have a different number in the different hydrogeological homogeneous areas.

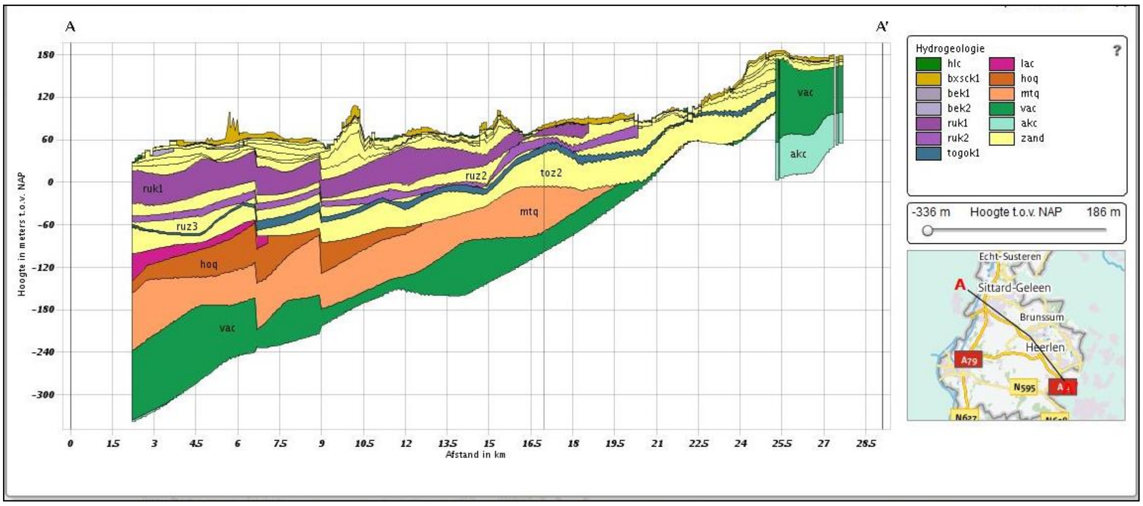

Fig. 39: Cross-section REGIS-II v2.1

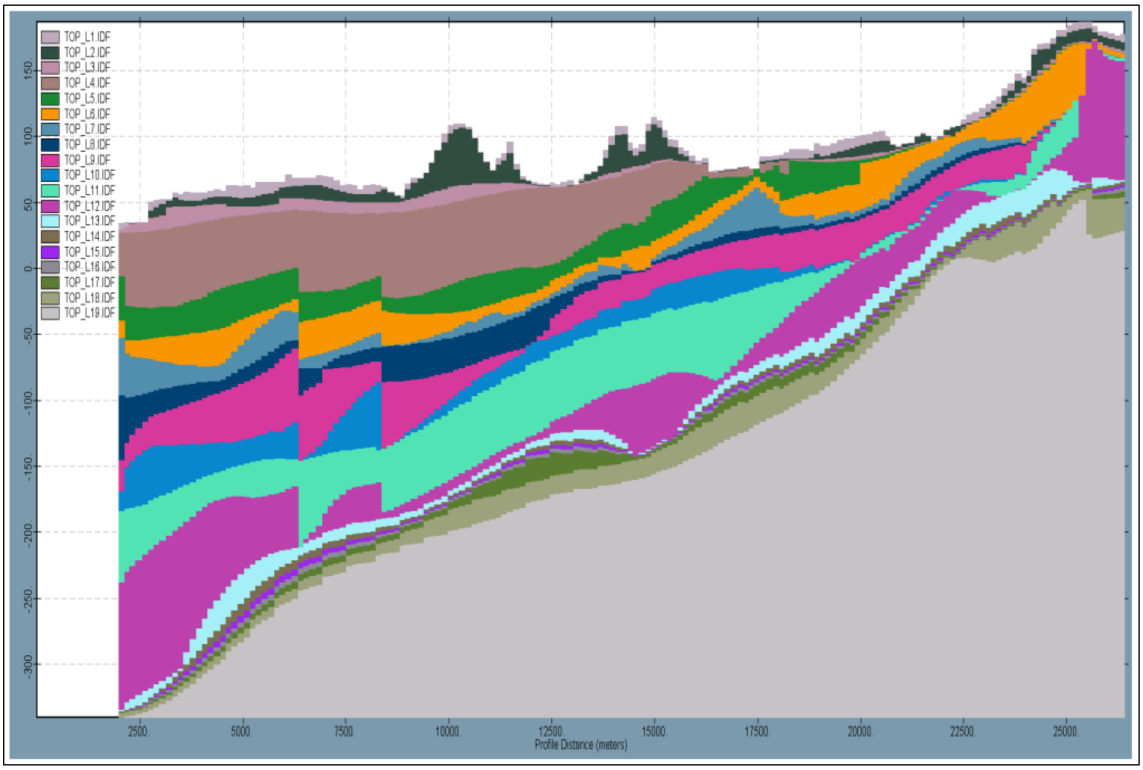

Fig. 40: Cross-section of the model layers in IBRAHYM

Tab. 4: Model layers IBRAHYM

Formation name	Aquifer or Aquitard	Model layer south of the Heerlerheide fault	Model layer between the Heerlerheide fault and the Feldbiß fault	Model layer north of the Feldbiß fault
Holocene		1	1	1
Boxtel	Aquifer	1	1	1
Beegden	Aquifer	2	2	4
Kiezelooliet clay 1	Aquitard	not present	not present	12
Kiezelooliet clay 2	Aquitard	not present	not present	13
Kiezelooliet clay 3	Aquitard	not present	not present	14
Kiezelooliet clay 4	Aquitard	not present	not present	15
Kiezelooliet clay 5	Aquitard	not present	not present	16
Frimmersdorf	Aquitard	not present	15	17
Morken	Aquitard	3	16	18
Rupel clay 1	Aquitard	4	not present	not present
Rupel clay 2	Aquitard	5	17	18
Tongeren	Aquifer / Aquitard	6	18	not present
Landen	Aquitard	7	not present	not present
Houthem	Aquifer	8	*	not present
Maastricht	Aquifer	9	*	not present
Gulpen	Aquifer	10	not present	not present

* These layers are present north of the Heerlerheide fault, but not integrated in the IBRAHYM model because of their limited thickness

The layers 1-2 (phreatic groundwater) and 9 (limestone aquifer) represent the main aquifers of the hydrogeological system.

6.3 Elaboration of the groundwater model

- Carboniferous

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, the Carboniferous has to be added to the model. 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).

The mining was mainly carried out up to approximately 20 m below the overburden. In some parts upward drilling took place to explore the distance between the basement and the overburden. Both layers, the basement above the mining zone and the mining zone, have been given a conductivity of $1 \cdot 10^{-3}$ m/d.

- Integration of the mine workings

A large part of the concessions was mined. The conductivity in the Carboniferous has to be adjusted according to the hydrogeological conditions. The areas with mining works are located in model layer 21.

Different literature shows different values for the hydraulic conductivity of the unmined Carboniferous (PAAS, 1997, GD NRW, 2011, WALLBRAUN, 1992, DE MAN, 1988, JÄGER et al., 1990). In the groundwater model IwanH, which has been developed especially for South Limburg, the Carboniferous has been given a conductivity of $1 \cdot 10^{-3}$ m/d. Values given in literature indicate a conductivity between 10^{-8} and 10^{-10} m/d.

There is very little data on the hydraulic conductivity of the mined Carboniferous formation, but based on literature and the pumping tests that were carried out for the mine water project in Heerlen, it is assumed that the conductivity is relatively high because of the galleries and the loosened rock. In the model the calculations were carried out with a conductivity of 250 m/d. Sensitivity analysis demonstrated that the hydraulic conductivity of the mined Carboniferous is not a major influencing factor on the heads in the Carboniferous.

- Hydraulic windows

During the active mining period, areas with a large inflow of groundwater from above were known, like the Douvergenhout event (DE MAN, 1988). This event describes a situation in 1930 where groundwater from the overburden flowed toward the Emma mining district (discharges starting at 2,5 m^3/min). According to DE MAN (1988) the reason was the existence of a hydraulic connection between Devonian sandstone, the sandy Tongeren layer and the Maastricht layer (limestone). Areas with large inflow from the overburden documented in the mine maps (“hydraulic windows”, Fig. 41) are taken into account in the model. These areas are assigned to model layer 20 with a conductivity of 5 m/d.

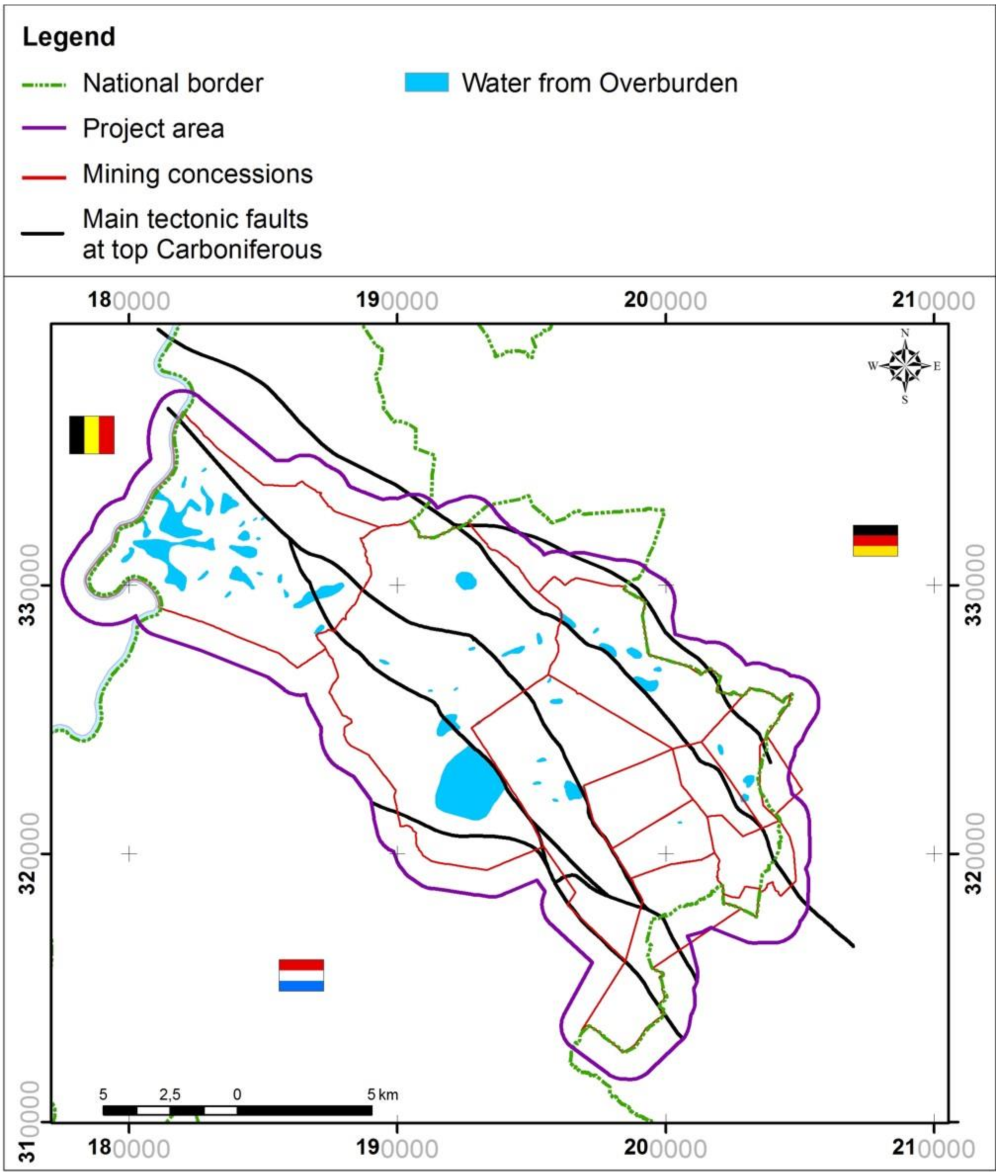

Fig. 41: Areas with a large amount of water from overburden documented in the mine maps (SHGM, 1975)

6.4 Modelling scenarios

All scenarios are steady-state calculations. The outcome of the calculations represents the future equilibrium situation of groundwater heads, after the rise of mine water has ended.

A sensitivity analysis was performed with the groundwater model to define the three scenarios. The goal of the analysis was to determine which factors mostly 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 highly influential.

Due to the strong spatial variations in the hydraulic conductivity of the Carboniferous formation, the effects of a high and low hydraulic conductivity were investigated. Additionally, the effect of a lower and higher recharge rate was investigated. A high recharge rate occurs when there is a large amount of groundwater flow under the Wurm, originating from the German mining area, that feeds the Carboniferous formation. A low recharge rate occurs when it is assumed that only the Dutch regions contribute to the total recharge to the Carboniferous.

This analysis has led to the definition of three scenarios for the final state when the mine water rise finishes, and a reference scenario:

- Reference model/scenario: This is the current situation, in which groundwater levels are calculated in the layers overlying the Carboniferous (overburden). The reference scenario is calculated with the current version of the IBRAHYM model and is calibrated using long term average groundwater levels.

- Worst case scenario: Mine water will rise to its highest level. The maximum level is determined by the discharge/drainage capacity of the Wurm river in the eastern part of the research area. The Wurm river has a reference elevation of about 110 mNAP. The presence of the Wurm and the rebuilt mine galleries in the Wurm river valley prevent groundwater levels from rising beyond this elevation.

  It was investigated under which conditions (i.e. for which hydraulic parameters of the Carboniferous formation) such a rise in groundwater levels was possible, and how much water must infiltrate from overlying formations and from precipitation in the regions where the Carboniferous reaches the surface. Additionally, it was tested whether this was a realistic scenario.

- Best case scenario: In this scenario, it was investigated what the amount of mine water level rise would be assuming a relatively high hydraulic conductivity for the Carboniferous formation. The recharge to the Carboniferous only originates from a narrow zone around the Wurm, yielding a relatively low amount of recharge. The combination of a narrow zone in which recharge occurs and a high hydraulic conductivity results in relatively low mine water level in the future. It was tested whether this was a realistic scenario.

- Average case scenario: In this scenario, the level of mine water rise was determined assuming a low hydraulic conductivity of the Carboniferous formation and a large amount of recharge. The area in which recharge to the Carboniferous takes place was assumed to include parts of the German mining area.

6.4.1 Present state/Reference scenario

The reference scenario is a steady-state calculation of the reference model. The reference model is the 2015 IBRAHYM model provided by the water boards and water company. In this model/scenario, also referred to as scenario 0, the Carboniferous has not been added to the model yet. The results of the calculations are shown in Fig. 42 and Fig. 43.

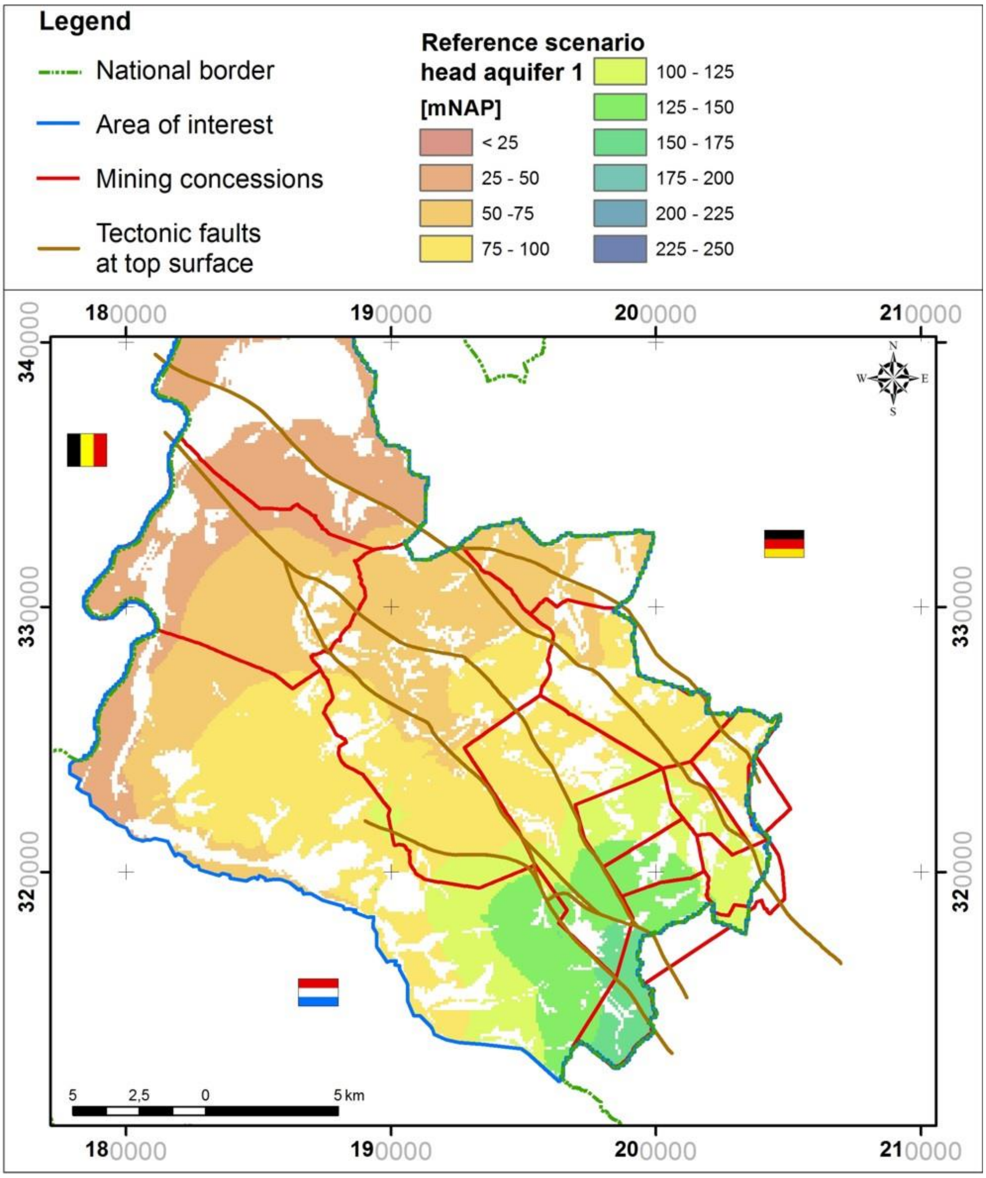

Fig. 42: Calculated heads in aquifer 1 (near-surface) - reference Scenario

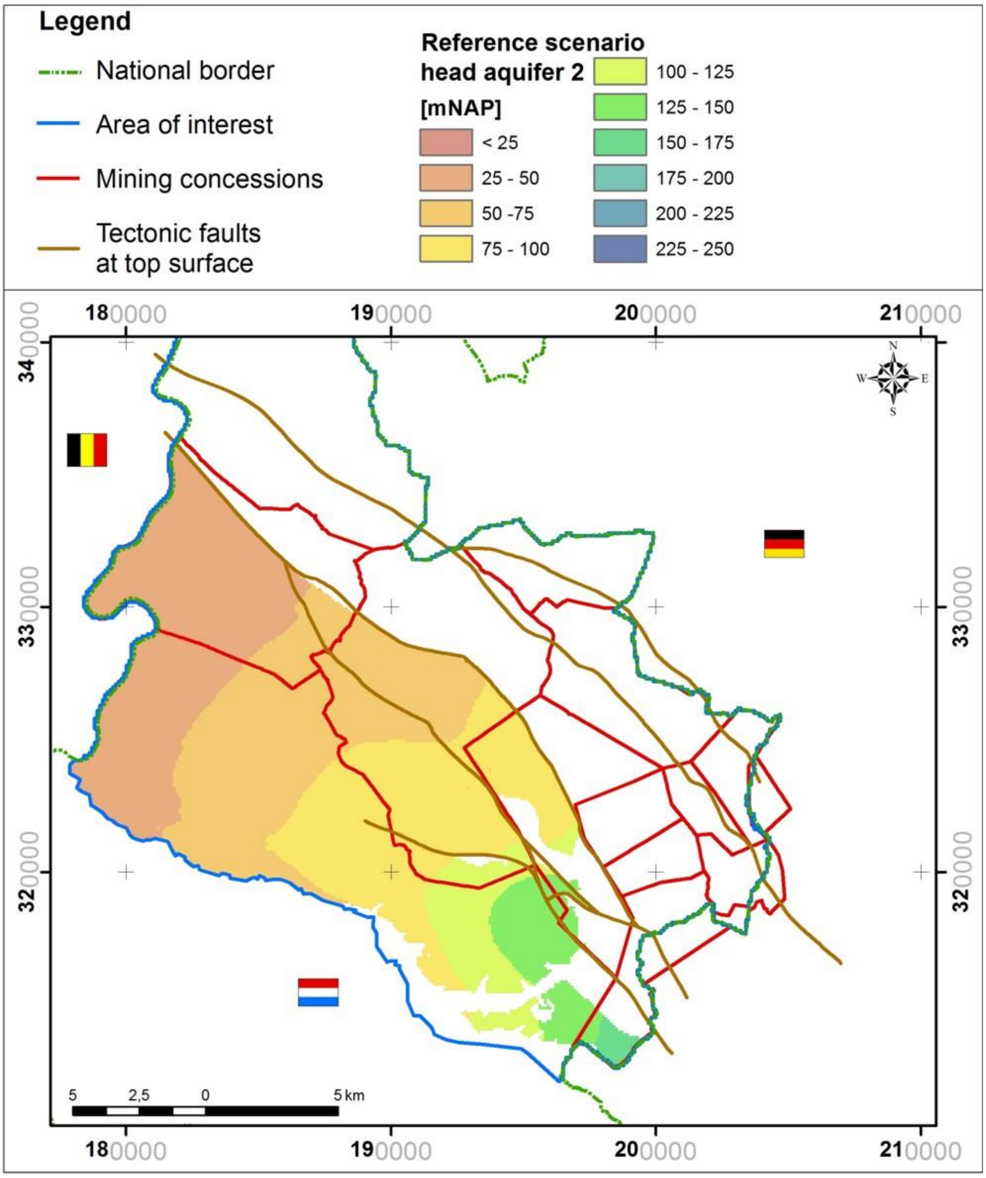

Fig. 43: Calculated heads in aquifer 2 (limestone) - reference Scenario

6.4.2 Final state

With the stationary groundwater model the final state is investigated. For all three scenarios it was investigated whether the scenario is likely to happen.

In the worst case scenario it was approximated that the rising mine water near the Wurm river would reach a maximum of 110 mNAP. Above this level, the water will be discharged/drained by the Wurm river. Only to the west of the Wurm there are small areas in which higher hydraulic heads can occur. Under which conditions this situation could occur was studied with the IBRAHYM model.

Calculations show this situation can only take place when the hydraulic conductivity of the Carboniferous is low, and the recharge rates in the contributing area are high. The requisite recharge to the Carboniferous in this situation was calculated to be a factor 50 higher than is expected considering the characteristics of the subsurface and the size of the recharge area. Therefore the probability of the worst case scenario to happen can be considered to be very small.

In the best case scenario it was approximated that the recharge to the Carboniferous is very limited and that the conductivity of the Carboniferous is relatively high. The recharge is defined by a specific amount of inflow into the Carboniferous in the Wurm Valley. This situation was studied with the IBRAHYM model. Calculations show this situation results in relatively low pressures compared to other scenarios. Therefore the probability of the best case scenario to occur can be considered to be very small.

In the average case scenario a realistic recharge is assumed. Therefore the conductivity of the mined Carboniferous is assumed to be lower than in the worst- and best case scenario, i.e. 50 m/d. In this scenario, a no flow boundary was modelled. The maximum head at the boundary is calculated and not defined in the model like the worst and best case scenario.

As a result the model calculates a more realistic recharge into the Carboniferous. The average case scenario is assumed to be the most realistic scenario.

- results average case scenario

In this scenario, the head in the Carboniferous in the eastern concessions will rise to a maximum of about 80 mNAP. Between the Emma and Maurits concessions lies an unmined zone which operates as a hydraulic barrier. Therefore, the hydraulic gradient between Emma and Maurits is very large. In the Maurits concession, the calculated heads in the Maurits concession are about 40 to 50 mNAP.

The results of the average case scenario calculations are shown in Fig. 44, Fig. 45 and Fig. 46 below.

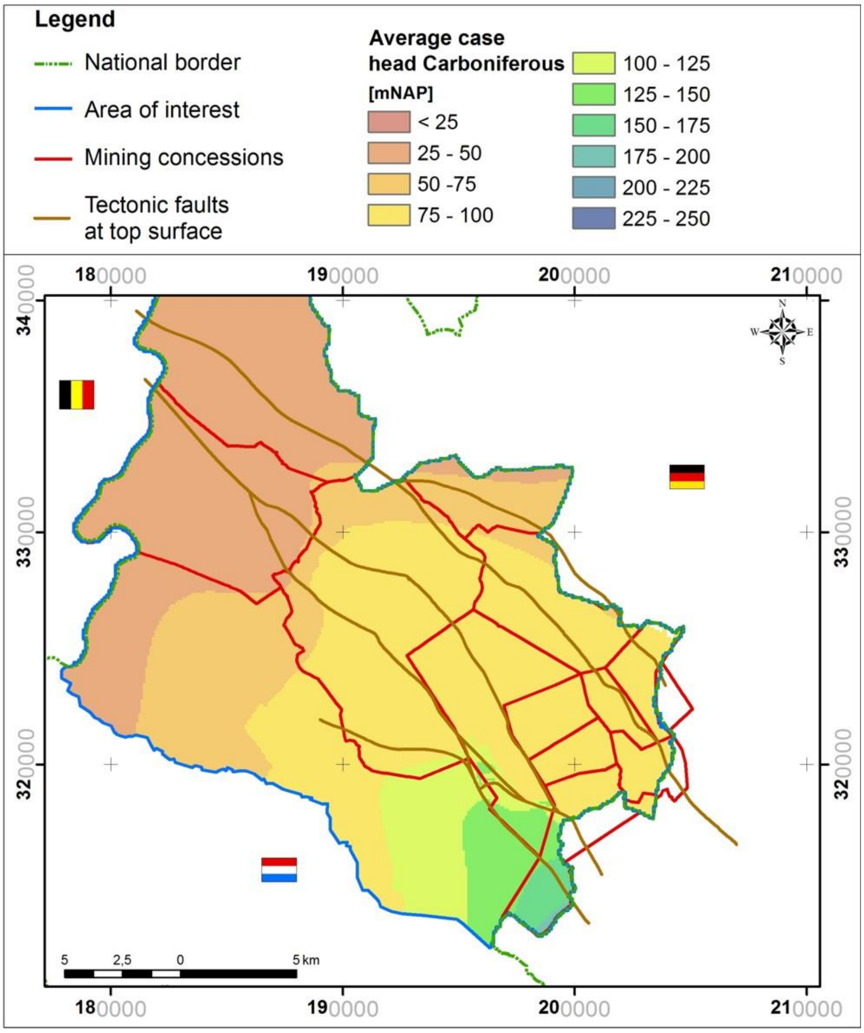

Fig. 44: Mine water pressure in the Carboniferous - average case scenario

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. 45). In the Maurits concession, increases of 0,25 to 0,5 m are calculated.

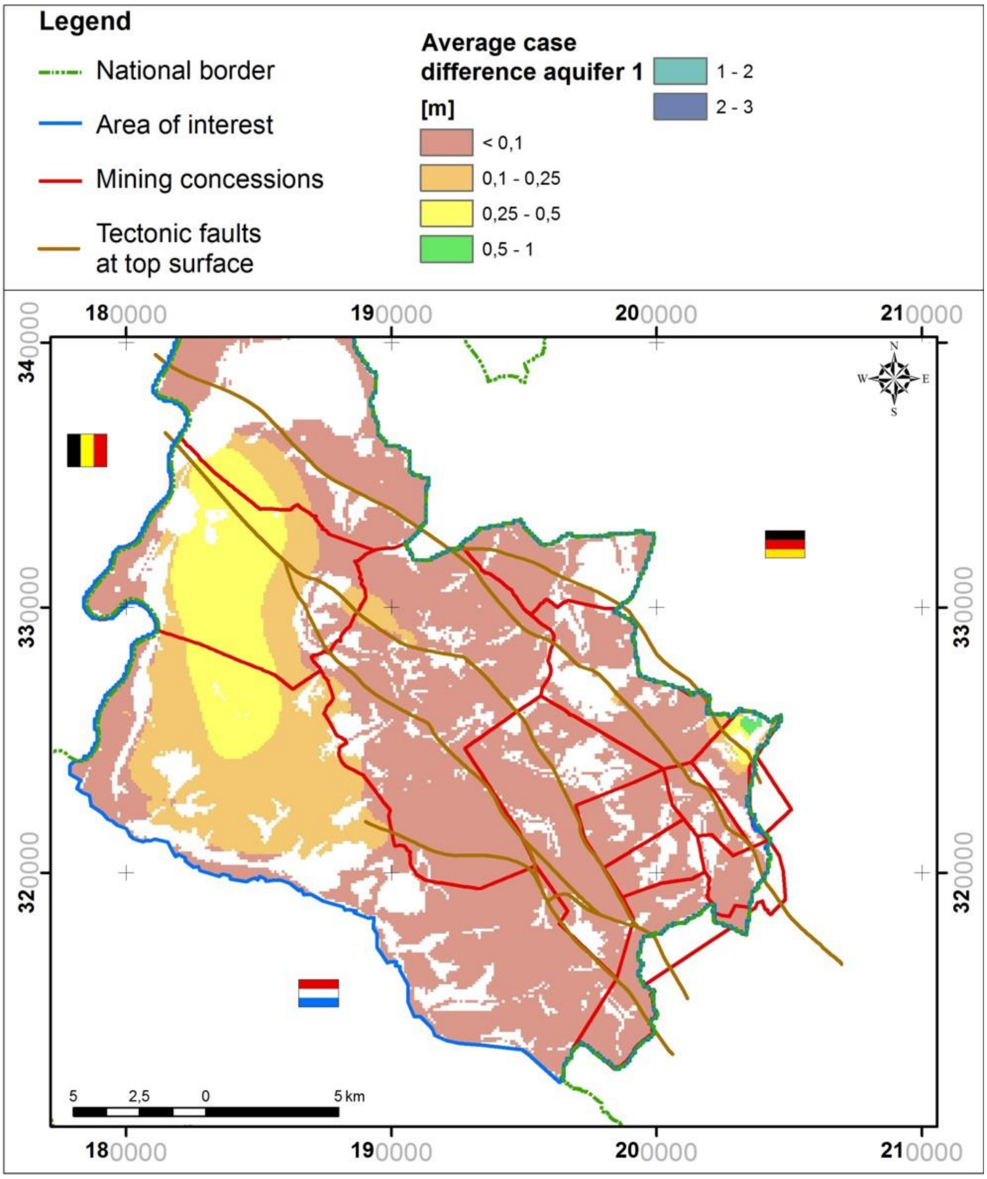

Fig. 45: Difference in phreatic groundwater table - average case scenario

The calculated rise of the (confined) water pressure (or groundwater head) 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. 46). In the Emma concession, the maximum groundwater pressure increase is calculated to be 1 m.

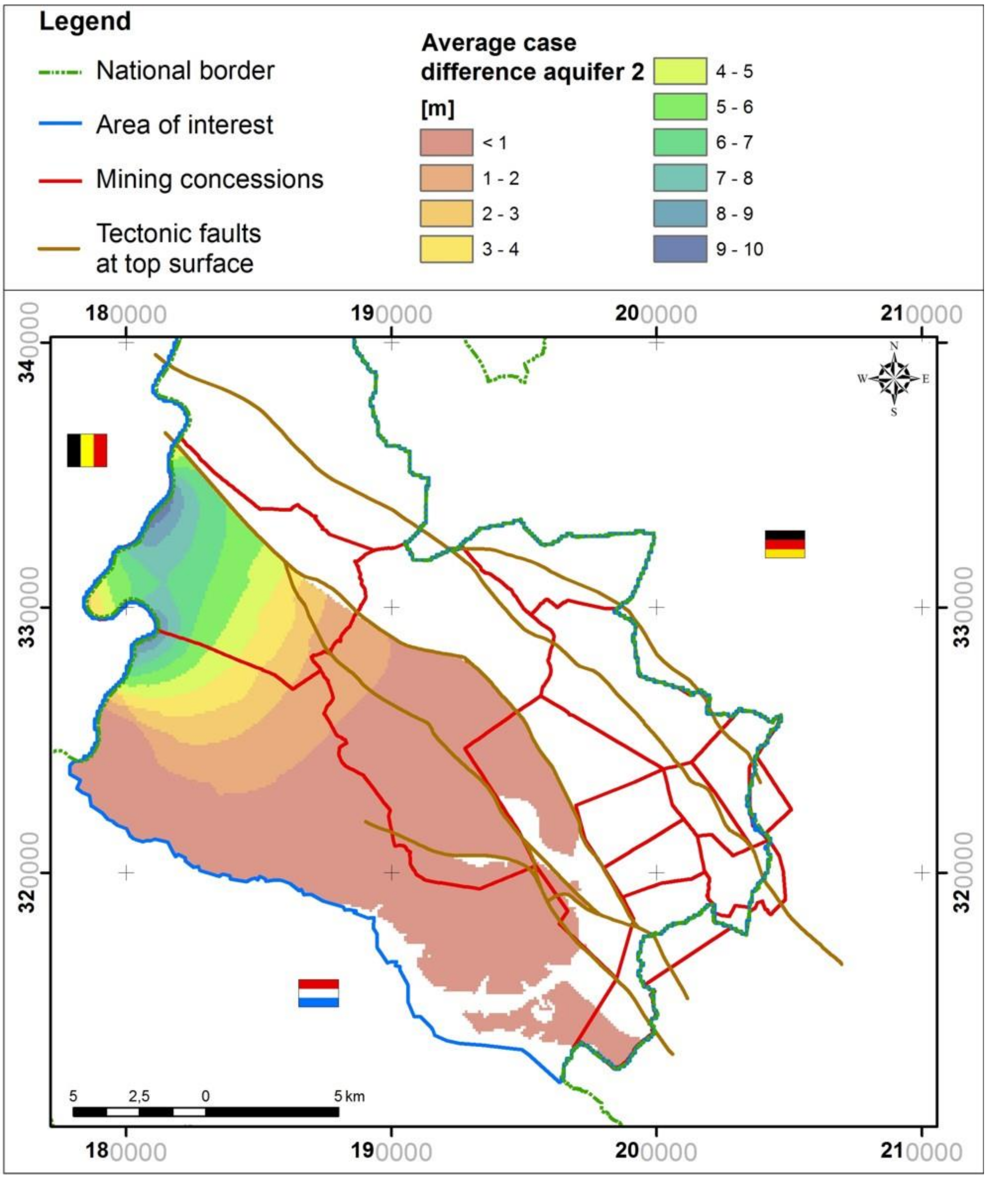

Fig. 46: Increase of groundwater head in second aquifer - average case scenario

- results worst case scenario

In the worst case scenario a rise of the mine water up to 110 mNAP in the Wurm valley is assumed. In this modelling scenario, a fixed groundwater head of 110 mNAP is applied to the upper layer of the Carboniferous (layer 20) in the Wurm valley. The area with the fixed head is shown in Fig. A3.1 (Appendix 3).

As a result of the fixed head at 110 mNAP and the high conductivity of the mined areas in this scenario the head of 110 mNAP reaches into the Emma concession (Fig. A3.2, Appendix 3). In the Maurits concession, the calculated mine water heads lie between 25 mNAP and 50 mNAP.

The rise of the mine water results in an increase of the groundwater level in the upper aquifer. The largest effect is visible in the eastern mine concessions (Julia, Hendrik, Laura, Domaniale, and Neu Prick). In these regions, an increase between 0,5 and 3,0 m of the groundwater table is calculated in respect to the reference scenario (Fig. A3.3). In the Maurits concession, increases of 0,25 to 0,5 m are calculated.

The calculated rise of the (confined) water pressure (or groundwater head) in the limestone aquifer (aquifer 2) with respect to the reference scenario reaches maximum values up to 9 m in the Maurits area (Fig. A3.4, Appendix 3). In the Emma concession, the maximum groundwater pressure increase is calculated to 2,2 m.

- results best case scenario

For the best case scenario the natural inflow of groundwater to the Carboniferous as a result of groundwater recharge is simulated. The amount of inflow is defined as the amount of natural recharge coming from the infiltration area in Germany, which has a surface area of 14 km^2. For this area, the specific recharge is 5,3 m^3/min.

The calculated pressures in the Carboniferous are lower than the pressures calculated in the worst case scenario for the Emma and the other southeastern concessions. In most of the southeastern concessions, pressures are calculated to be between 50 and 75 mNAP (Fig. A3.5, Appendix 3). In the Maurits area, pressures lie between 25 and 50 mNAP.

For the first aquifer the calculated rise related to the reference scenario is smaller than in the worst case scenario especially in the eastern concessions but quite comparable to the average case scenario. Overall, the maximum effect is a head increase of about 0,5 m (Fig. A3.6, Appendix 3).

The head calculated in the limestone aquifer (aquifer 2, Fig. A3.7, Appendix 3) shows large differences, between 5 and 9 m in the valley of the river Maas, which is similar to the results in the worst case scenario. In the eastern concessions Emma and Oranje Nassau I, III, IV, the calculated rise of the groundwater head is less than 1 m.

7 Assessment of the impact potential

7.1 Introduction

The estimation of areas that might be affected by the impacts of rising mine water provides the basis for the further risk analysis. Based on model calculations, two areas of influence are defined for

- wetting and for
- changes in groundwater quality.

The 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.

7.2 Potential Impact Areas

7.2.1 Wetting

The areas of influence are based on calculations performed with IBRAHYM. The calculations showed that rising mine water in parts of the research area will cause increases in hydraulic head in layers in the overburden. This is in agreement with measurements carried out with the mine water monitoring network.

The increase of the head in the Carboniferous, which is completely saturated (flooded), has resulted in a decrease in infiltration from the overburden over the last few decades. This has caused an increase in the head in the overlying layers, which is also seen in the measurements obtained by the mine water monitoring network. The increase in head subsequently influences the head in the more shallow layers, but due to the presence of semi-permeable layers (aquitards, layers with a low hydraulic conductivity) the increase is small.

In large parts of the research area the groundwater table is found at a larger depth (more than 3,5 m below the surface level). The calculated increase of the groundwater level (aquifer 1) in the average scenario lies between 0,25 and 0,5 m, mainly in the Maurits concession and partly in the Julia concession. In areas with a higher groundwater table, generally observed in the “beekdalen” (valleys), a smaller increase of the groundwater level is calculated, with increases up to 0,1 m.

The depth of the groundwater table is approximated at 3,5 m below the surface level because it is assumed that an (limited) increase in heads in layers with deeper groundwater level will not lead to possible damage to agriculture, nature, infrastructure or structures with basements.

The largest calculated increase in the phreatic groundwater level of 0,5 m occurs in the Maurits and Julia concessions in areas where the groundwater table lies well below 3,5 m below the surface. This increase will therefore not lead to water nuisance.

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. In the worst case scenario, wetting could occur in other Valleys, like the Rode Beek and Anselderbeek.

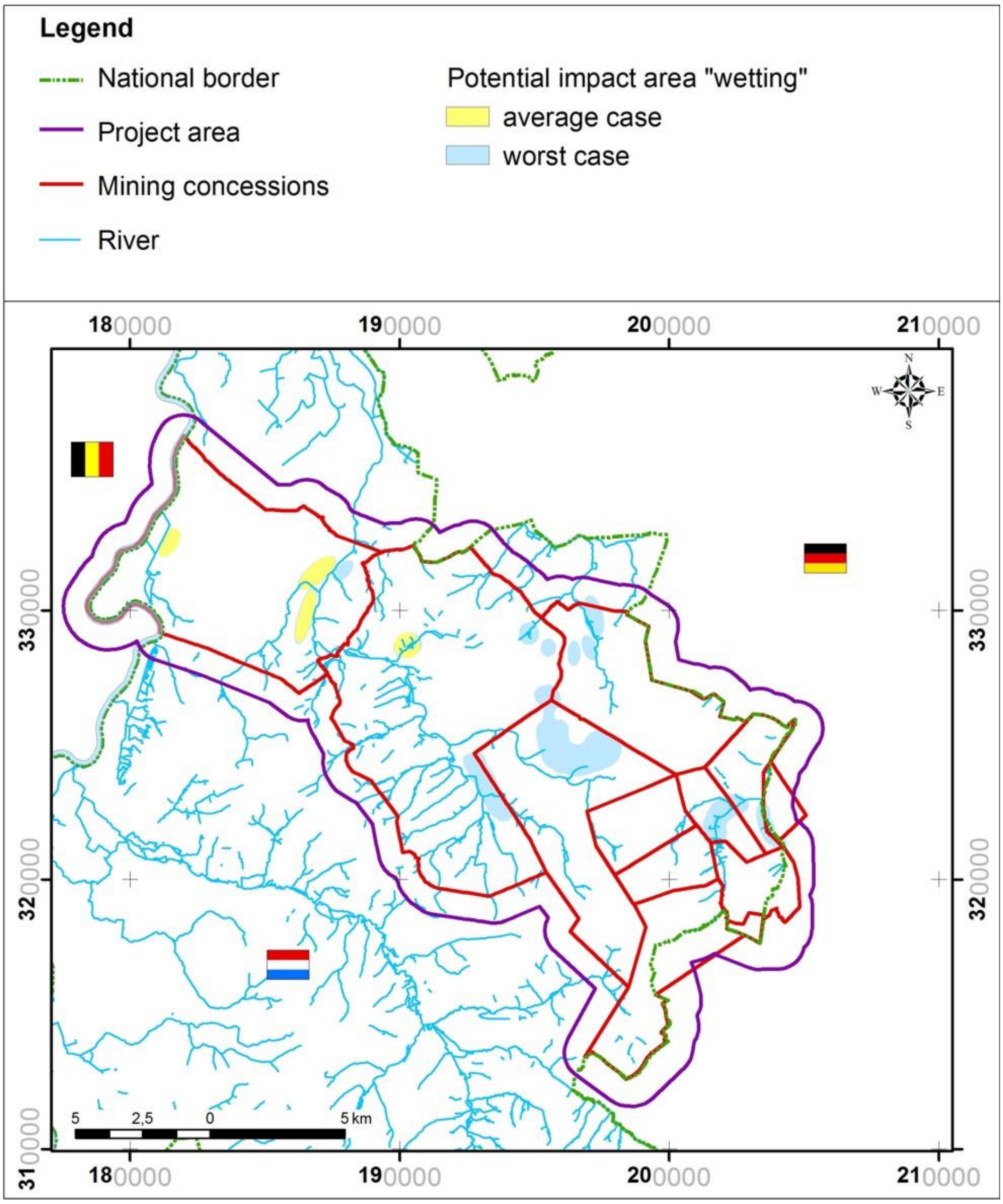

Fig. 47: Potential impact areas “wetting”

7.2.2 Groundwater quality

The potential areas of influence for a change in groundwater quality are also calculated with IBRAHYM. 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 of the head of the mine water is higher than the water levels in the shallow aquifers. 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. The profiles below show in which areas an upward or downward flux is expected, based on model calculations.

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 Fig. 48; see Fig. 49 and Fig. 50):

- 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.

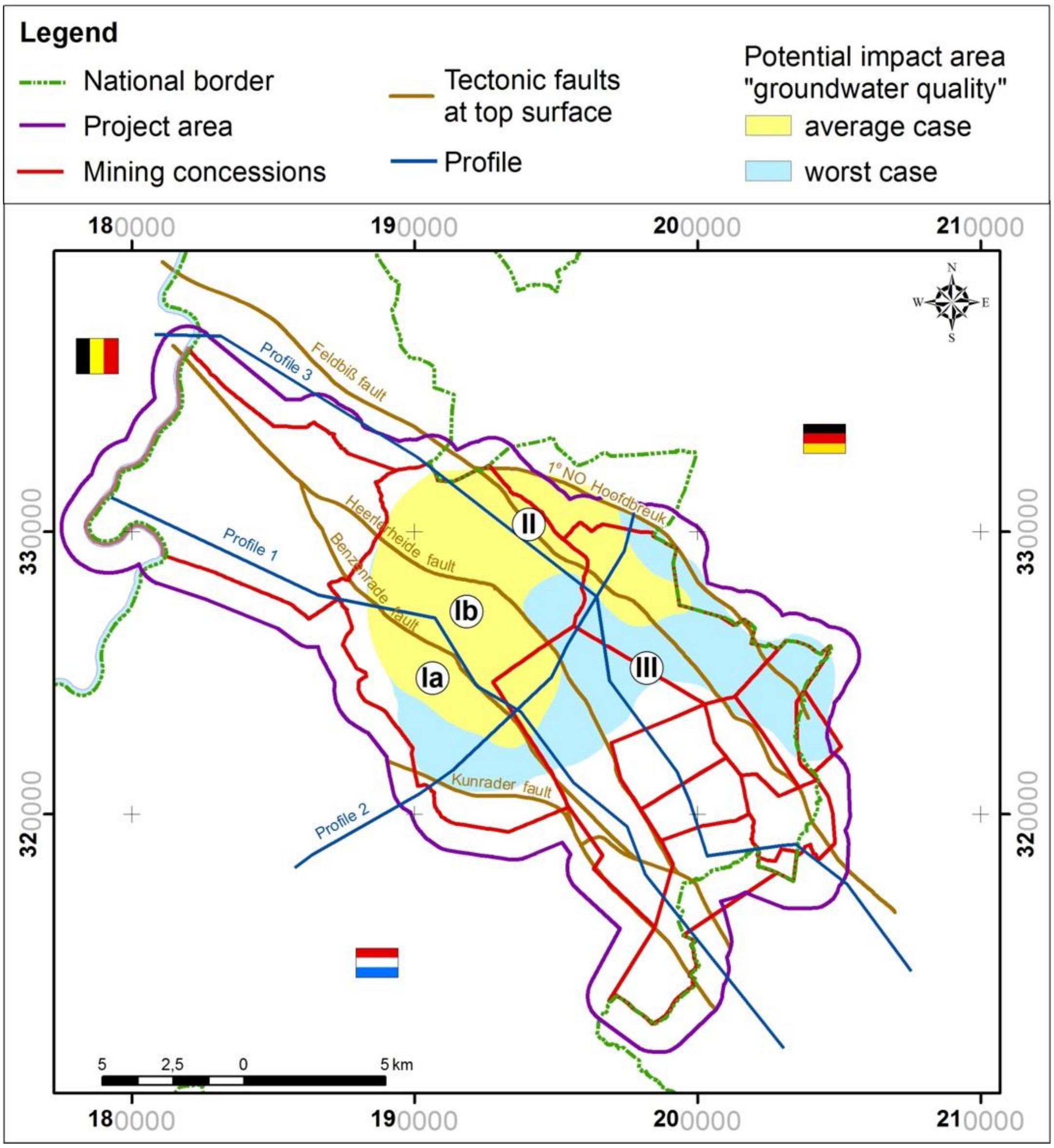

Fig. 48: Potential impact areas for change of groundwater quality

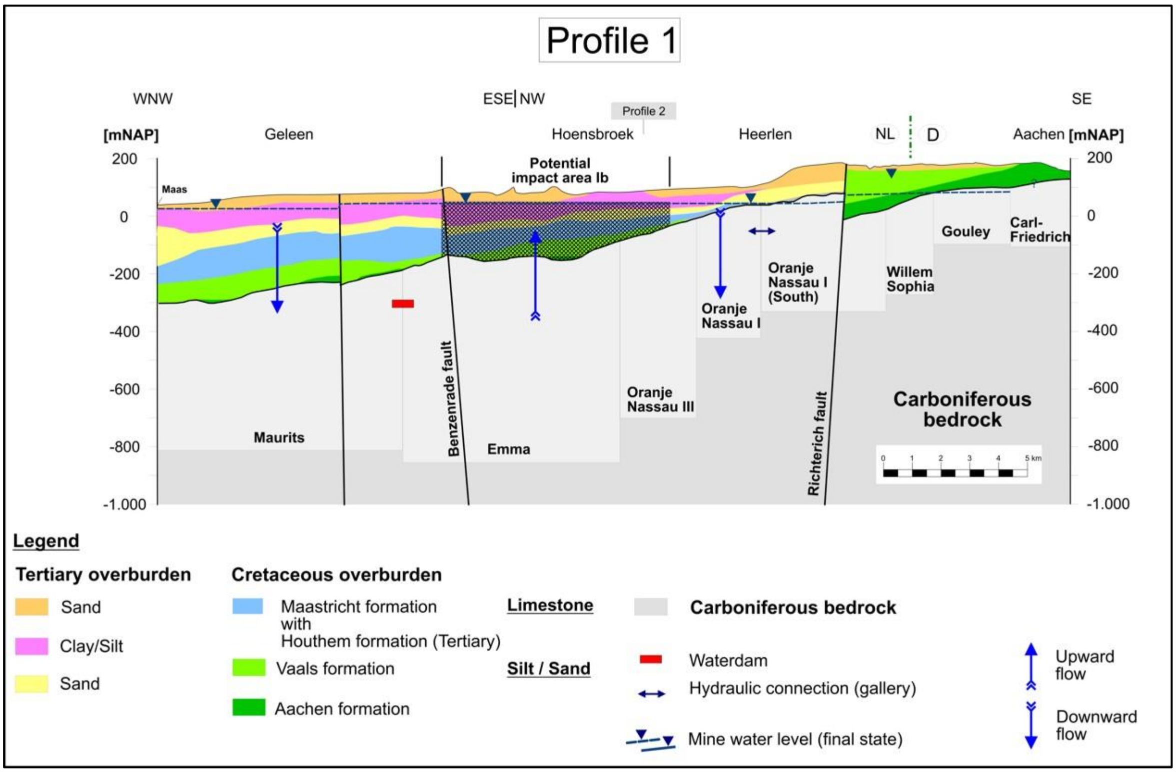

Fig. 49: Potential impact area near profile 1 (shown schematically)

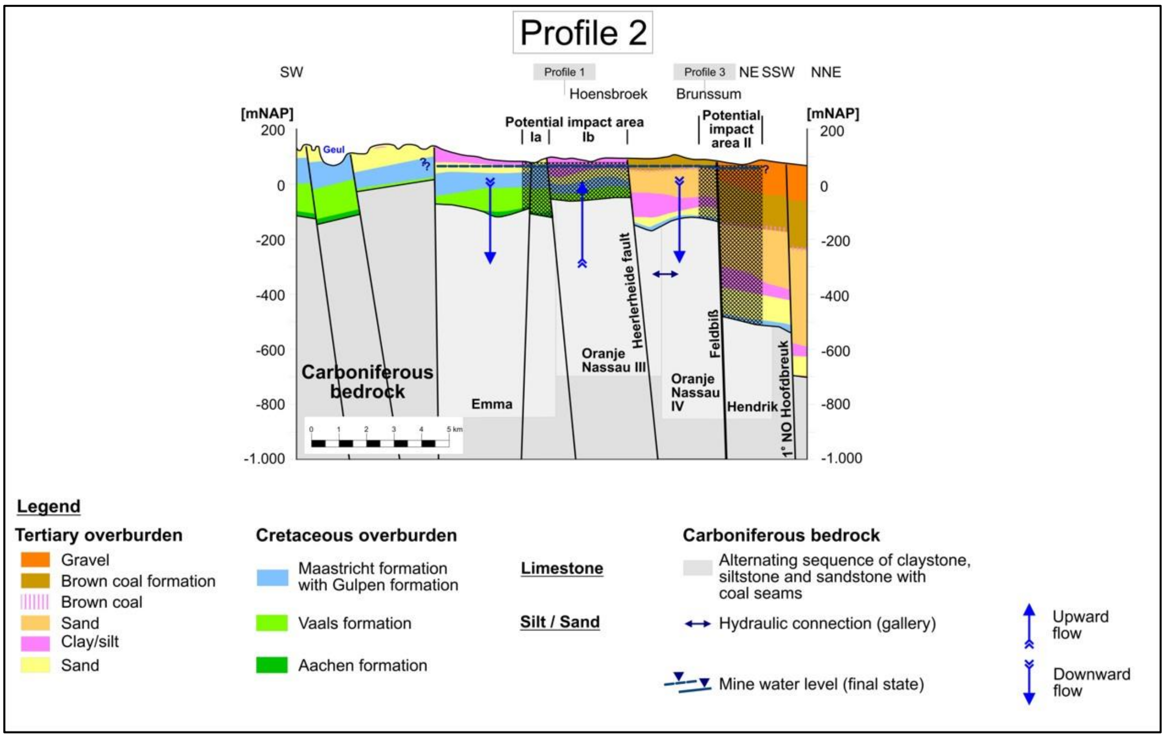

Fig. 50: Potential impact area near profile 2 (shown schematically)

Furthermore a potential impact area III (blue area in Fig. 48) is calculated considering the worst case scenario. As discussed in chap. 6.4 this is a highly unlikely scenario, but out of a scientific point of view it cannot be excluded totally.

7.3 Potential impacts on groundwater quality

7.3.1 Approach

The volume of mine water that flows from the Carboniferous into the overlying aquifers in the potential impact areas, how long this process takes, and what changes in groundwater quality this causes is mainly dependent on the geohydrological characteristics/properties of the subsurface.

As indicated, mostly the top 20 m of the Carboniferous formation was not mined, and can be considered as an important aquitard providing resistance to upward flow. This is not the case everywhere, however. In some regions the 20 m zone is not intact because of upward drillings, mine shafts, local mine workings, or naturally occurring zones with a higher hydraulic conductivity (“hydraulic windows“; Fig. 41). These hydraulic connections form so-called “threats” that cause the rise of deep groundwater levels and the subsequent impact of that rise on the quality of shallow groundwater levels (Fig. 51).

In the modelling process the effect of hydraulic windows on groundwater flow was researched by introducing these windows into the model and applying a low hydraulic conductivity. The hydraulic resistance of the layers overlying the Carboniferous was also taken into account. The individual drillings and shafts were not included in the model, mainly because these local connections also have a very local effect on the groundwater level.

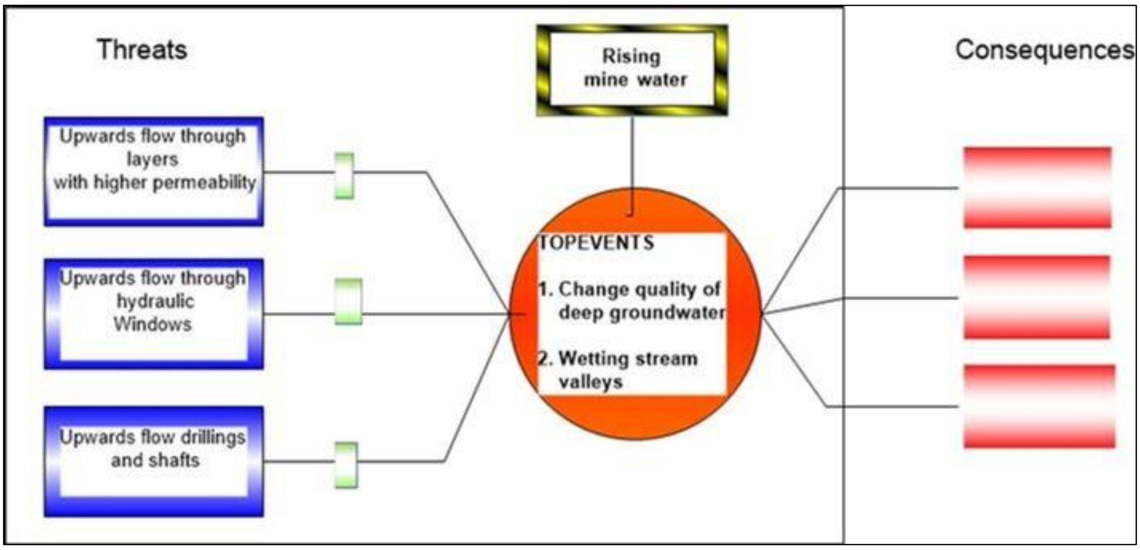

Fig. 51: Bow-Tie-Analysis - Threats triggering quality change and wetting

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:

- First the problem is analysed; possible effects on groundwater quality were identified. Based on the model schematisation the flow paths and travel time of mine water were determined.
- Then, 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.
- The third step was to calculate the ratio of mine water and groundwater using the 3D transport model MT3DMS.

- The fourth step was to perform a hydrogeochemical simulation of mine water flowing upwards with the PHREEQC programme.
- The final step was to calculate the chloride concentration using the 3D transport model MT3DMS.

7.3.2 Analysis of possible effects on groundwater quality

In the potential impact area I, mine water flows from the top layer in the Carboniferous aquifer, through the Vaals/Aachen sandy formation into the limestone aquifer, where groundwater extractions are situated (Fig. 52). Tab. 5 shows the characteristics of these layers.

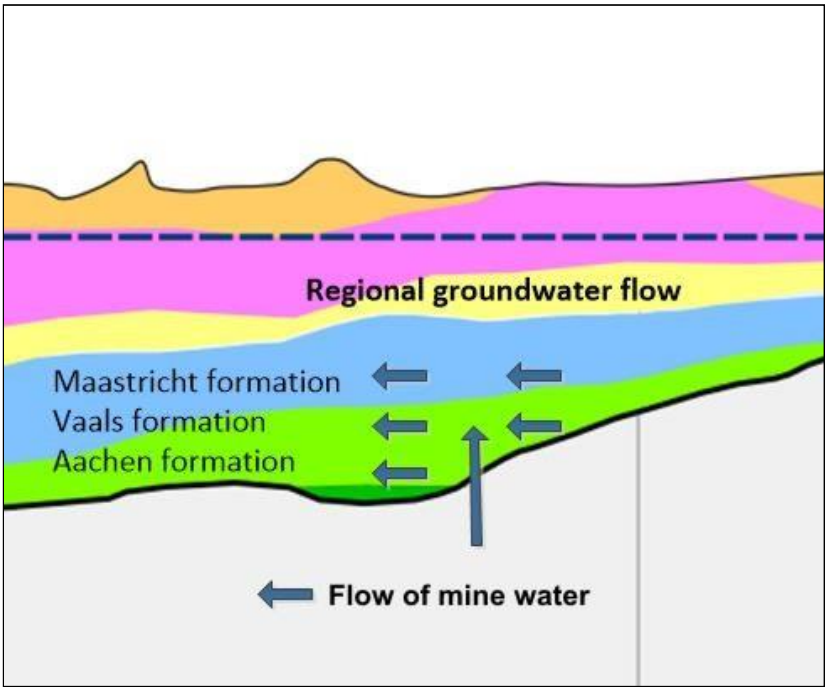

Fig. 52: Mine-/Groundwater flow paths in potential impact area I

Tab. 5: Characteristics flow path Carboniferous-Aachen/Vaals- Maastricht/Gulpen

Formation	Characterisation	Activities	Hydraulic characteristics	Thickness at potential impact areas
Maastricht/Gulpen	limestone	Groundwater extraction wells	k_h = 5 - 10 m/day in upper part till 0,01 m/day for deeper limestone layers	Ia ca. 20 - 60 m Ib ca. 30 - 40 m
Vaals	fine to very fine sands, loamy to clayey	none	Kv = 0,001 m/day Porosity = 0,3 (assumed)	Ia 50 - 60 m Ib 30 - 40 m
Aachen	alternation of fine sand layers with layers consisting of black/grey clay	none	Kv=0,001 m/day Porosity = 0,3 (assumed)	Ia < 10 m Ib 0 m
Carboniferous	Carboniferous	Former mining activities	due to mining activities a high transmissivity is assumed	

To calculate the expected travel time for mine water between the top of the Carboniferous layer to the bottom of the Maastricht/Gulpen layer, the head difference between these two layers is read out of the model results. The worst- and average case model have been used.

In Tab. 6 an overview is given of the calculated head difference between the Carboniferous and Maastricht/Gulpen, for both scenarios. The difference is presented for the two potential impact areas.

The travel distance (distance between top Carboniferous and bottom Maastricht/Gulpen), is extracted from the groundwater model for the two locations.

Tab. 6: Head difference between top Carboniferous and bottom Maastricht (limestone aquifer)

Potential impact area	Calculated head difference between Carboniferous and Maastricht (limestone aquifer)	
	average case	worst case
	[m]	[m]
Ia	3	14
Ib	5	25

Now, using the hydraulic characteristics from Tab. 6 the travel times are calculated. The result is shown in Tab. 7.

Tab. 7: Calculated travel times

Potential impact area	Calculated travel times	
	average case	worst case
	[a]	[a]
Ia	1.750	370
Ib	1.050	200

Tab. 7 gives a first indication of the possible risk in the two defined areas. In areas Ia and Ib there is a risk of mixing of mine water and groundwater. First (indicative) calculations indicate that the highest risk is in the centre of Emma concession.

In these calculations it is assumed that there are no hydraulic windows and that the hydraulic conductivity of the unmined layer between the Carboniferous and the Aachen and Vaals formations is still present.

In the next paragraph a water balance analysis is described to determine the scale of mixing (i.e. what amount of mine water will mix with fresh groundwater) near hydraulic windows.

7.3.3 Water balance analysis of effect on groundwater quality

In the previous chapters the upward flowing of mine water has been described. Using the water balance tool from the groundwater model the relative amount of mine water that reaches the Maastricht/Gulpen layer can be determined. In every layer mixing takes place with regional fresh groundwater. This process is shown schematically in Fig. 53.

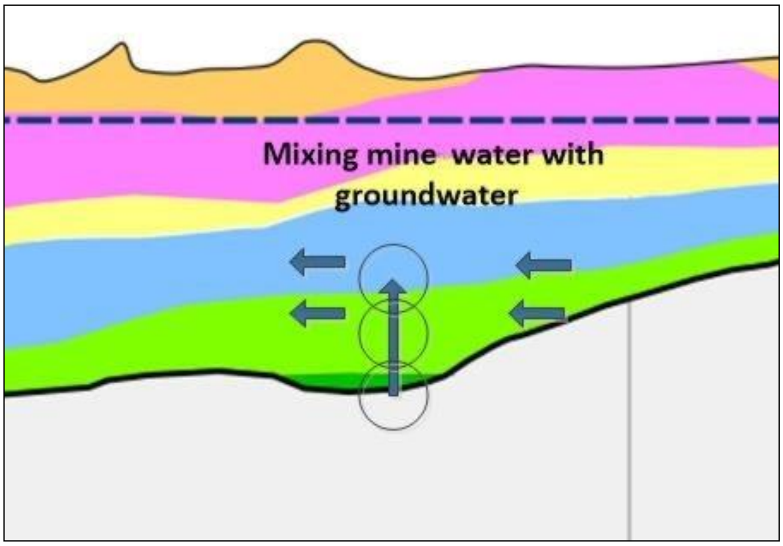

Fig. 53: Schematic presentation mixing of mine water with groundwater

The water balance for both the worst case model and the average case model has been analysed. This is done for the two different areas. For each of these areas the vertical flux and the horizontal flux is extracted from the worst case groundwater model as well as from the average case groundwater model. To determine the maximum fraction mine water entering the aquifer the following basics have been used:

- the concentration mine water in the top of the Carbon layer is set to 100 %;
- the concentration mine water in the layers above is initially set to 0 %;
- thus the natural groundwater has a mine water concentration of 0 %;
- mixing takes place in the complete water balance area;
- in the layer in which the wells are located, all water flowing towards the well is natural groundwater not influenced by mine water except for the vertical flux, which comes from the layers underneath;
- the presented result is based on steady-state situation, and is therefore the result of indefinite mixing;
- no processes such as retardation due to adsorption or dispersion are taken into account.

In this way the maximum fraction mine water in the aquifer is estimated. Since no geochemical processes are taken into account this is to be considered as a worst-case from the geochemical point of view. Tab. 8 shows the results of the water balance analysis.

From the water balance analysis it follows that the highest risk is at potential impact area Ib. In this area the groundwater model calculates the largest vertical flux.

Tab. 8: Summary of results

Well location	maximum fraction mine water in wellfield	
	average case	worst case
	[%]	[%]
Potential impact area Ia	0,1	1,1
Potential impact area Ib	0,5	24,8

7.3.4 Transport model analysis of effect on groundwater quality

Since estimating the fraction of mine water to enter the wells in the defined potential impact areas based on the water balance method can easily overestimate this fraction, additional calculation have been made with a transport model.

Based on the groundwater model such as described in chap. 6 this 3D transport model is created. The transport model is based on the IBRAHYM groundwater model. The transport model can be used to calculate concentrations based on the calculated groundwater head and -fluxes. With these calculations processes such as dispersion can be taken into account.

In the transport model, in the Carboniferous layers a “mine water concentration” of 100 % is assigned to the complete Carboniferous layer.

Using the transport model the distribution of mine water and chloride can be calculated for a selected time period. In this case, a time period of 100 years is set. Fig. 54 shows the result for mine water.

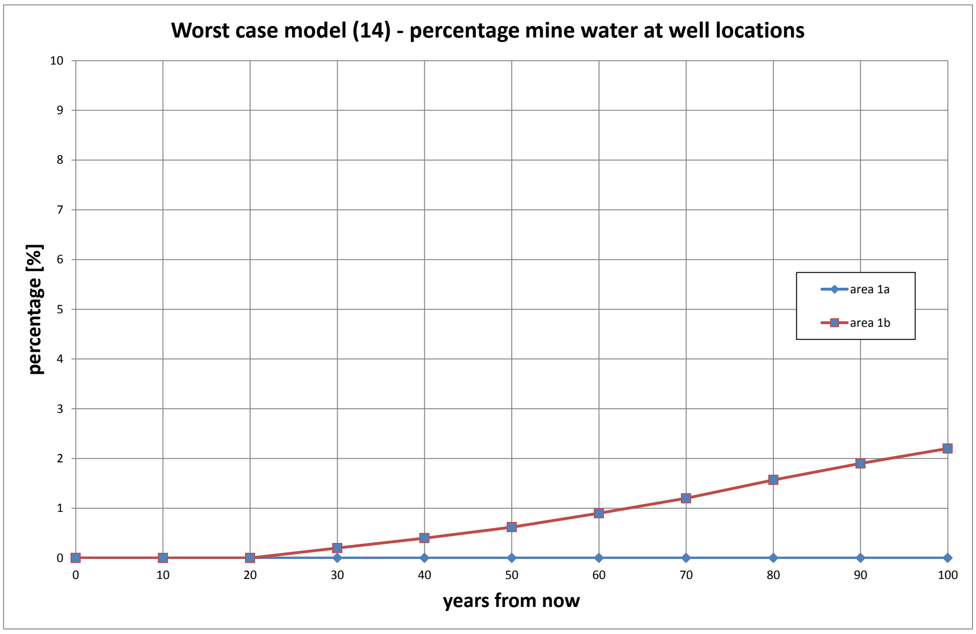

Fig. 54: Percentage mine water at wellfields in area Ia and Ib

In area Ia there is no significant influence of mine water calculated in wellfields in this area. The maximum concentration of mine water is calculated in area Ib, north of Benzenrade fault and south of the Heerlerheide fault after 100 years: approximately 2,5 % of mine water is calculated in the aquifer.

This result corresponds with the result of the water balance analysis: area Ib it is most likely that a fraction of mine water eventually enters the aquifer. The calculated fraction is approximately 2,5 %. This is much lower than the fraction that has been calculated with the water balance analysis (25 %). The difference is most likely due to the worst case approximation that has been used in the water balance calculation.

Based on the water balance and transport calculations three scenarios are defined for hydrogeochemical simulations with the PHREEQC programme (Tab. 9). The potential fraction mine water is based on the high end expectations, in order not to underestimate possible impacts of mine water on shallow groundwater wells.

Tab. 9: Mixing scenarios abstraction wells

Scenario	fraction mine water	dilution factor	Remarks
1	1,0 %	0,01	maximum expected contribution of mine water to extracted water at area Ia
2	2,5 %	0,025	- worst case area Ia, - maximum expected contribution of mine water to extracted water, area Ib
3	25 %	0,25	worst case, area Ib (based on water balance calculations)

7.3.5 Hydrogeochemical simulations

The chemical composition of mine water is quite different from the groundwater in the aquifers of areas Ia and Ib. Along the flow path between the coal seams of the Emma concession and groundwater wells at areas Ia and Ib water quality will change due to different hydrogeochemical processes. Estimation of the potential impact of mine water on the quality of abstracted groundwater at potential impact areas Ia and Ib is divided in 5 steps, following the source-path-threatened-object method:

- Define mine water quality (source)
- Estimate groundwater quality change top Carboniferous (path)
- Estimate groundwater quality change in Aachen/Vaals formation (path)
- Estimate groundwater quality change in Maastricht formation (path)
- Estimate groundwater quality change in future abstraction wells (threatened object)

Groundwater travel time between coal seams and abstraction wells is calculated with MODFLOW. Mixing fractions between mine water and groundwater are quantified with MODFLOW. The PHREEQC programme (www.usgs.gov) is used to quantify the expected change in water quality due to hydrogeochemical processes along a flow path (1D-model).

- Mine water quality

Water quality in mines is influenced by pyrite-oxidation, since mine water was abstracted and the mines were vented. This will result in mine water with high sulphate content and a low pH (acidic). The mine water is therefore probably enriched with trace metals. Chloride content of mine water is influenced both by deep thermal water and water from the above lying layers and is in the range of

150 - 1.400 mg/l for areas Ia and Ib. Mine water composition is generated with PHREEQC. The following assumptions are made (see Tab. 10):

- Groundwater composition of the sample “Emma 54” (zone III), documented in KIMPE (1963) is used as characteristic composition for groundwater in the vicinity of coal seams;
- Oxygen is added to oxidise pyrite, simulating conditions in vented mines;
- Equilibrium with pyrite and goethite is assumed.

Pyrite oxidation causes high sulphate concentrations and acid conditions. Fe^{2+} (iron) will increase due to dissolution of pyrite, but when no more pyrite is available, it will oxidise to Fe^{3+} and precipitate as goethite. Chloride concentration is not influenced by pyrite oxidation.

Tab. 10: Generated quality mine water

Parameter		Mine water	
		Sample Emma 54 (from KIMPE, 1963) in vicinity of coal seam (measured)	in contact with oxygen (calculated)
pH	[-]	8,5	1,85
Ca	[mg/l]	14	14
Mg	[mg/l]	5	5
K	[mg/l]	16	16
Na	[mg/l]	1.204	1.205
Cl	[mg/l]	1.359	1.359
Fe^{2+}	[mg/l]	0	0
Fe^{3+}	[mg/l]	0	2
SO_4	[mg/l]	5	1.925
HCO_3	[mg/l]	949	949
EC-measured	[µS/cm]	4.770	
EC-calculated	[µS/cm]	4.948	10.389
Ionic balance error	[%]	-0,49	-0,38

Trace elements such as Cd, Zn, Ni, Sn, Cu, Cr, Co and As may be present in mine water, due to impurities of pyrite. Under acid conditions (pH < 4 to 5), heavy metals are very mobile. Arsenic is also mobile at higher pH-levels.

Water samples have been taken in the vicinity of mine waste rock tip ("mijnsteen"), showing these trace elements (WITTEVEEN+BOS, 2011; Tab. 11).

Tab. 11: Water samples of the Emma Mine waste rock tip (water samples from 2006, WITTEVEEN+BOS, 2011)

Parameter		Value
pH	[-]	4,58
EC	[µS/cm]	920
Arsenic (As)	[µg/l]	5,28
Cadmium (Cd)	[µg/l]	2,43
Chrome (Cr)	[µg/l]	0,51
Nickel (Ni)	[µg/l]	45,1
Zinc (Zn)	[µg/l]	105

- Groundwater quality change Top Carboniferous

Water quality is influenced by the mineral composition of the rocks and the water-rock interaction. Minerals that can be found in mine waste rock are clay-minerals, quartz, siderite, pyrite, halite, ankerite/Fe-dolomite, calcite, rutile, dickite, feldspar and chlorite (WITTEVEEN+BOS, 2011).

The most important minerals to be considered are sources of iron and carbonate minerals, which define the buffer capacity, such as pyrite, siderite, calcite and dolomite.

At top of the Carboniferous, in many places there is a clay layer, known as the Baggert (VAN ROOIJEN ADVIEZEN, 1998). This layer is represented by clay-minerals illite and chlorite. Calcite and dolomite are not abundant in this clay layer. In the PHREEQC calculations, it is assumed that these minerals are not present in this clay layer, to avoid overestimating of the buffer capacity of this layer.

Calculating the effect of buffering with PHREEQC, it assumed that equilibrium is reached between water and rock (no kinetics are taken into account because of the very slow transport of groundwater, less than 1 m/a). Gypsum, gibbsite and goethite are allowed to precipitate if oversaturated.

Through buffering, pH will change form acid to (nearly) neutral (6,78) conditions (Tab. 12). Since no calcite and dolomite buffering is assumed, calcium concentration is not changed when mine water comes in contact with the clay layer. Chloride concentration is not changed (significantly), because it doesn’t react with the minerals taken into account. Sulphate decreases, due to precipitation of pyrite. Aluminium concentration increases, due to weathering of clay minerals, but precipitates to gibbsite at neutral pH levels.

Tab. 12: Expected water quality at top Carboniferous

Parameter		Mine water at coal seams in contact with oxygen	Mine water arriving at top Carboniferous
pH	[-]	1,85	6,78
Ca	[mg/l]	14	14
Mg	[mg/l]	5	789
K	[mg/l]	16	0
Na	[mg/l]	1.205	1.213
Cl	[mg/l]	1.359	1.368
$Fe^{(2+)}$	[mg/l]	0	1
$Fe^{(3+)}$	[mg/l]	2	0
SO_4	[mg/l]	1.925	1.289
HCO_3	[mg/l]	949	4.041
Al	[mg/l]	0	0,0007
EC-calculated	[µS/cm]	10.389	8.995

- Groundwater quality change Aachen/Vaals formation

Passing through the Aachen (if present) and the Vaals formations, mixing will occur between water flowing upwards from the Carboniferous formation and water currently present is the Aachen/Vaals formation. Furthermore, interaction between rock and water will take place.

- Mixing waters

Groundwater quality at the top of the Carboniferous at areas I and II (Emma concession) before mine water rising can be described as a $CaHCO_3$-type (type I) or a $NaHCO_3$-type (Type II), based on KIMPE (1963), as described in ROSNER (2011). $NaHCO_3$-type occurs where Vaals sands are present with a significant thickness, resembling ion exchange related to glauconite sands. $CaHCO_3$-type occurs at the top of the Carboniferous layer for situations where the Maastricht limestone aquifer is more directly in contact with the top of the Carboniferous (impact area II, not to be considered here, due to absence of groundwater extractions in this area).

These water types are characterised by a high HCO_3-content (400 - 650 mg/l) and a high Ca or Na content. Chloride is low (< 20 mg/l), SO_4 is low (< 20 mg/l) and pH ranges from 7,8 - 8,7. Only a limited number of ions were analysed in KIMPE (1963).

These water types developed as a result of groundwater flow from Maastricht/Vaals layers downwards, towards the Carboniferous layer, driven by the abstraction of mine water. The water quality at the top of the Carboniferous is not influenced by mining activities in a situation before mine water rise occurs.

The PHREEQC programme is used to calculate the mixed water concentration between Vaals water and Carboniferous water (Tab. 13). Vaals water is represented by the “Emma 68” sample documented in KIMPE (1963). Oversaturated minerals are allowed to precipitate in this calculation.

Tab. 13: Calculated mixed water Carboniferous-Vaals

Parameter		Mine water arriving at top Carboniferous	Vaals water Sample Emma 68 (from Kimpe, 1963) (measured)	Mixed Mine water top Carboniferous - Vaals water
pH	[-]	6,78	8,7	6,9
Ca	[mg/l]	14	2	3
Mg	[mg/l]	789	0	395
K	[mg/l]	0	4	2
Na	[mg/l]	1.213	267	745
Cl	[mg/l]	1.368	18	699
$Fe^{(2+)}$	[mg/l]	1	0	0
$Fe^{(3+)}$	[mg/l]	0	0	0
SO_4	[mg/l]	1.289	19	659
HCO_3	[mg/l]	4.041	653	2.349
Al	[mg/l]	0,0007	0	0,0004
EC measured	[µS/cm]		924	
EC-calculated	[µS/cm]	8.995	1.078	5.022

More or less conservative mixing occurs mixing both waters.

- Minerals in Aachen/Vaals

The Vaals formation consists mainly of fine sands with glauconite and clay layers (“leem”). Glauconite is a secondary mineral, deposited in shallow water of marine origin.

The general formula of glauconite is $(K,Na)(Mg,Fe^{2+},Fe^{3+})(Fe^{3+},Al)(Si,Al)_4O_{10}(OH)_2$. The stoichiometry of glauconite is different across the world. Glauconite is associated with organic matter and calcite. It will degrade to clay minerals (montmorillonite). In the Vaals formation the most reactive components are probably calcite, dolomite, pyrite, montmorillonite, illite and organic matter.

It is assumed that an equilibrium is reached between water and minerals (no kinetics are taken into account due to the very slow transport of groundwater, 1 m/a or less). Degradation of organic matter is irreversible.

Sulphate concentration is decreased, due to changed redox conditions (Tab. 14). Potassium (K) concentration is increased, due to weathering of K-feldspar. Calculated pH is increased from 6,90 to 7,55.

Tab. 14: Expected water quality top Vaals

Parameter		Mixed Water Mine water Carboniferous / Vaals-water	Mine water arriving at the top of Vaals formation
pH	[-]	6,9	7,55
Ca	[mg/l]	3	25
Mg	[mg/l]	395	11
K	[mg/l]	2	56
Na	[mg/l]	745	750
Cl	[mg/l]	699	703
$Fe^{(2+)}$	[mg/l]	0	0
$Fe^{(3+)}$	[mg/l]	0	0
SO_4	[mg/l]	659	161
HCO_3	[mg/l]	2.349	573
Al	[mg/l]	0,0004	0,0032
EC-calculated	[µS/cm]	5.022	3.767

- Groundwater quality change Maastricht

Groundwater from the top of the Vaals formation enters the Maastricht limestone formation. The limestone formation consists of 50 to 95 % $CaCO_3$. Equilibrium with calcite is assumed (no kinetics). Calcite is more abundant than in the Aachen/Vaals formation. Water quality does not change significantly, because within the Vaals formation, the groundwater quality was already assumed to be in equilibrium with calcite (Tab. 15).

Tab. 15: Expected water quality Maastricht/Vaals

Parameter		Mine water at the top of Vaals formation	Mine water at Maastricht formation
pH	[-]	7,55	7,55
Ca	[mg/l]	25	25
Mg	[mg/l]	11	11
K	[mg/l]	56	57
Na	[mg/l]	750	751
Cl	[mg/l]	703	704
$Fe^{(2+)}$	[mg/l]	0	0
$Fe^{(3+)}$	[mg/l]	0	0
SO_4	[mg/l]	161	172
HCO_3	[mg/l]	573	574
Al	[mg/l]	0,0032	0,0032
EC-calculated	[µS/cm]	3.767	3.780

- Expected water quality area Ia and Ib

To identify the current groundwater quality of the Maastricht formation at areas Ia and Ib, measurements at the Craubeek wellfield are used. Water quality data for this Craubeek wellfields is available since 1970 for individual wells (WML, 1970 - 2014, only samples with an absolute ionic balance error < 10 %, n=200; Tab. 16). Chloride concentrations vary between 17 and 35 mg/l. Sulphate concentrations vary between 43 and 95 mg/l. Maximum nitrate concentration is 15,8 mg/l. Based on the average water quality, a characteristic water quality for the area I is calculated (Tab. 17). Iron is set to 0, because in most cases iron concentrations are (near) zero, if nitrate is present. Furthermore, the HCO_3 concentration is recalculated to minimise the ionic balance error.

Tab. 16: Measured water quality abstraction Wells Craubeek

Parameter		Minimum	Maximum	Average water quality
pH	[-]	7	7,6	7,2
Ca	[mg/l]	122	170	141
Mg	[mg/l]	2,7	14,1	8,9
K	[mg/l]	1	6	2
Na	[mg/l]	3	7,6	5,7
Cl	[mg/l]	17	35,5	23,9
$Fe^{(2+)}$	[mg/l]	0	15	0,4
NO_3	[mg/l]	0,5	15,8	5,1
SO_4	[mg/l]	43	95	67,5
HCO_3	[mg/l]	320	370	344,8
EC-calculated	[µS/cm]	485	805	651

Tab. 17: Characteristic shallow groundwater quality

Parameter		Average measured water quality area Ia and Ib	Assumed characteristic water quality area Ia and Ib
pH	[-]	7,2	7,2
Ca	[mg/l]	141	141
Mg	[mg/l]	8,9	8,9
K	[mg/l]	2	2
Na	[mg/l]	5,7	5,7
Cl	[mg/l]	23,9	23,9
$Fe^{(2+)}$	[mg/l]	0	0 (set to 0)
NO_3	[mg/l]	5,1	5,1
SO_4	[mg/l]	67,5	67,5
HCO_3	[mg/l]	344,8	384,3 (recalculated)
EC-calculated	[µS/cm]	651	
EC-calculated	[µS/cm]		740
Ionic balance error	[%]		0,0

- Mixing of water at the abstraction wells

Groundwater, originated at the coal seams flows upwards and reaches the abstraction wells after a period of more than 50 years. Mixing of water types in the formations traversed occurs. Based upon the MODFLOW mixing-calculations the effects of scenarios are calculated: expected “average” case, and worst case, both for areas Ia and Ib. The scenarios are given in Tab. 9. Results of these scenarios are given in Tab. 18; in red concentrations exceeding the maximum measured values for a period without mine water influence are indicated.

For scenario 1 (area 1a), expected chloride concentration is slightly above the measured maximum value, but below the “drinkwater norm” (150 mg/l). For the scenarios 2 chloride concentration is higher, but below 100 mg/l.

For the “worst case north of the Benzenrade fault” (area Ib, scenario 3), chloride concentration is 365 mg/l. Compared to the other scenarios chloride concentrations are high, due to a higher assumed upward flux in this worst case scenario. Chloride is an inert element and does not react with rocks, but is only influenced by mixing with other waters. The calculated concentrations are directly linked to the assumed chloride concentration in mine water (1.359 mg/l).

Sodium (Na) is expected to increase, but is expected to stay below 100 mg/l. Sulphate concentration is expected to increase slightly, but will stay below the “drinkwater norm” (150 mg/l), for scenario 1 and 2. In the worst case scenario north of the Benzenrade fault (scenario 3) the concentration of sodium, sulphate and carbonates are above the maximum measured values.

Tab. 18: Results scenarios water quality change at wells Craubeek

Parameter		Craubeek water quality	Mine water in Maastricht formation	Mixing scenario 1 area 1a (average case)	Mixing scenario 2 area 1a (worst case) area 1b (average case)	Mixing scenario 3 area Ib (worst case)	Measured maximum value 1970-2014, ionic balance error <10 %
pH	[-]	7,2	7,6	7,2	7,3	7,5	7,6
Ca	[mg/l]	141,1	24,6	138,8	135,3	82,9	170,0
Mg	[mg/l]	8,9	11,0	8,9	9,0	9,9	14,1
K	[mg/l]	2,0	56,5	3,1	4,7	29,4	6,0
Na	[mg/l]	5,7	751,1	20,7	43,1	379,5	7,6
Cl	[mg/l]	23,9	704,2	37,6	58,0	365,2	35,5
Fe	[mg/l]	0,0	0,0	0,0	0,0	0,0	15,0
NO_3	[mg/l]	5,1	0,0	2,7	0,0	0,0	15,8
SO_4	[mg/l]	67,5	171,8	79,5	93,3	130,7	95,0
HCO_3	[mg/l]	384,3 *)	574,2	388,2	394,0	480,0	370,0

***)** recalculated, already above maximum value
in red colour: concentrations exceeding the maximum measured values

- Heavy metals

Mobility of most heavy metals depends on pH (amongst others). A large change in pH is not to be expected, pH will stay in the range 7,0 to 7,5, so mobility of metals is limited. Besides low mobility, dilution plays an important role in the expected concentration in the abstracted wells; the expected fraction for mine water relative to “shallow groundwater” is 0,01 to 0,025. It is not to be expected that measurable concentrations of trace elements from mine water will be detected in the abstracted water.

The expected development of the groundwater quality along a flow path from the coal seams to the shallow groundwater at the wellfields is summarised in Fig. 55 for some critical parameters. Mine water pH is below 2 and rises fast along the flow path to a value between 7 and 8. Chloride and sulphate concentration both decrease along the flow path from values between 1.250 and 2.000 mg/l towards values below 100 mg/l at the shallow wellfields in the chalk aquifer.

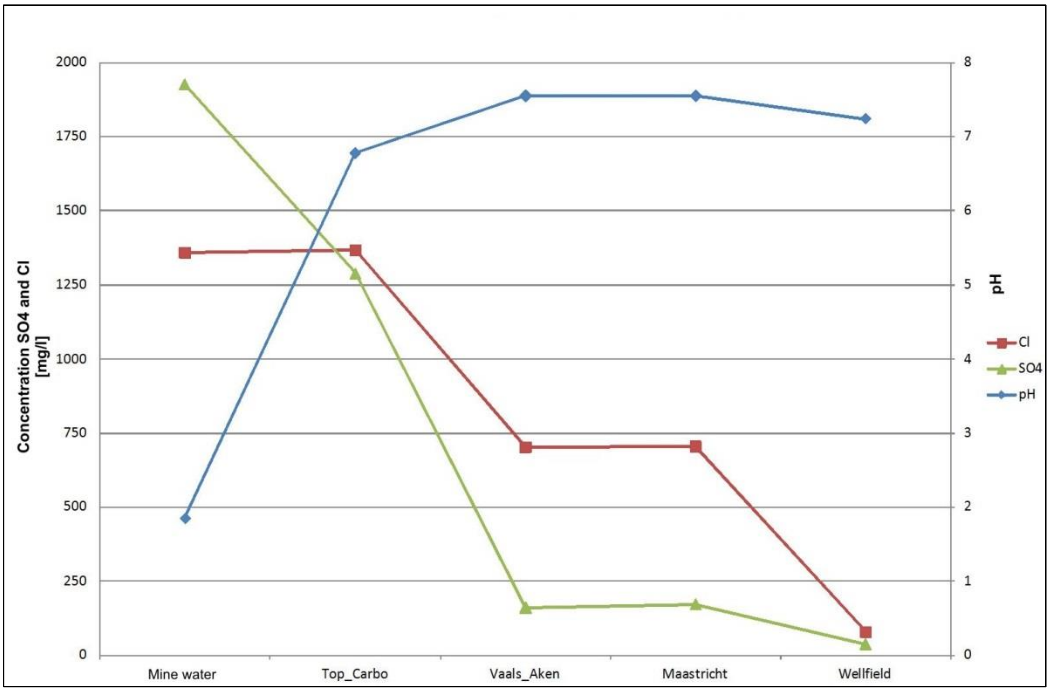

Fig. 55: Development groundwater quality between coal seams and wellfield, scenario 1

Fig. 56 shows the expected development of groundwater quality for scenario 2. The calculated values at the wellfields are higher than for scenario 1, but are still below 100 mg/l for chloride and sulphate. The expected groundwater quality at the wellfields for scenario 3 are higher than for scenarios 1 and 2 (Fig. 57). A chloride concentration of 365 mg/l is calculated, and for sulphate the expected concentration at the wellfields is 131 mg/l. Based on the 1D PHREEQC calculations, chloride is identified to be the largest threat for the groundwater quality in the Maastricht aquifer.

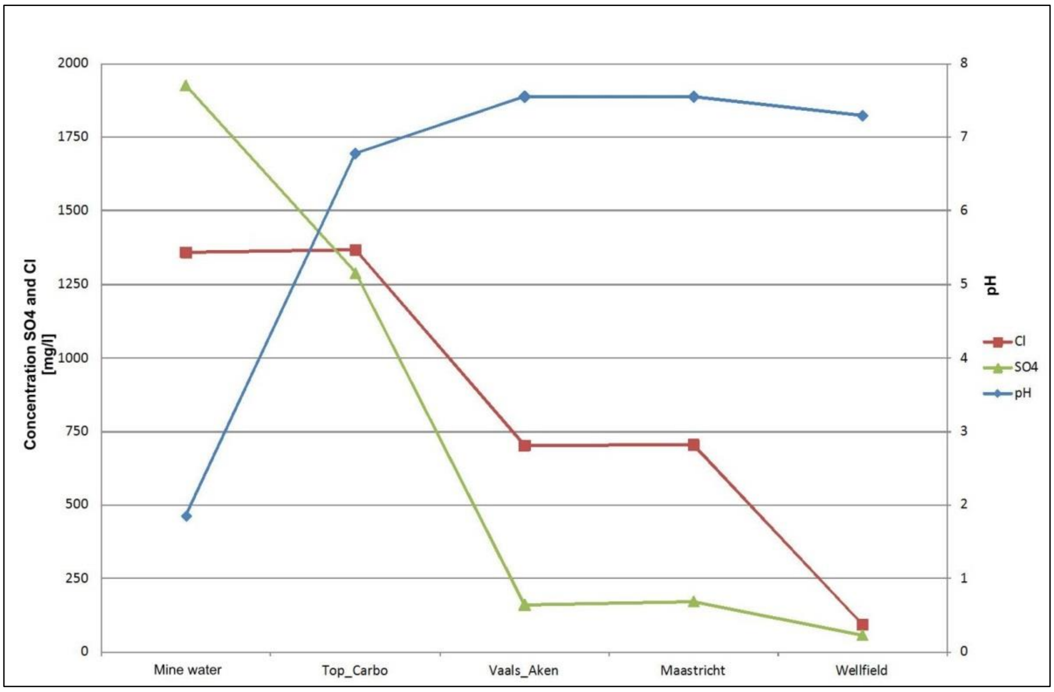

Fig. 56: Development groundwater quality between coal seams and wellfield, scenario 2

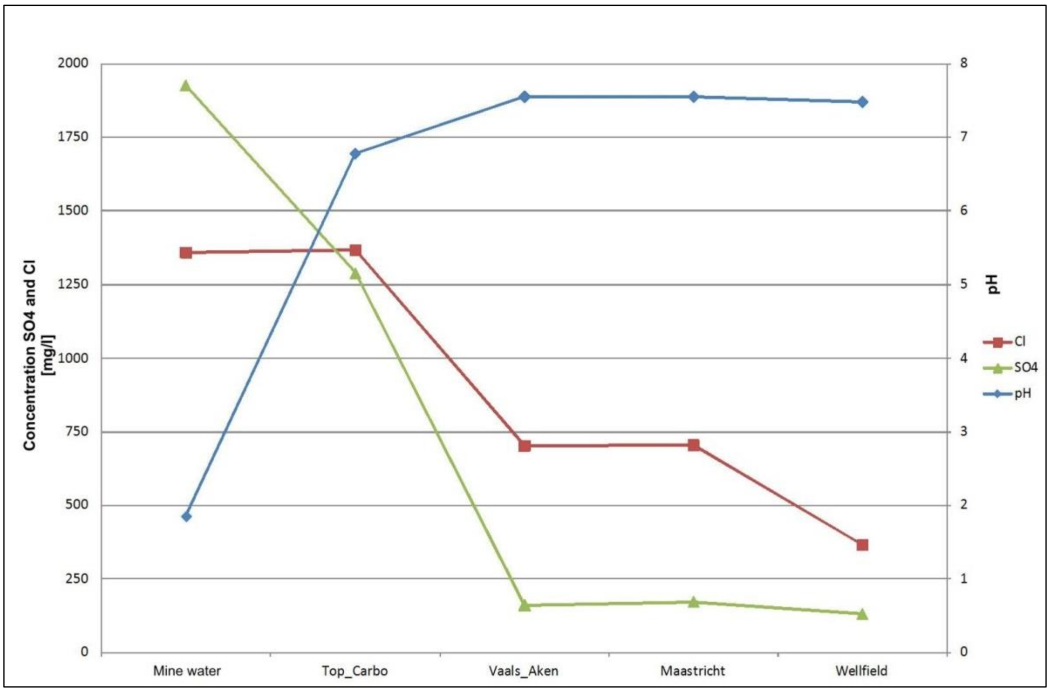

Fig. 57: Development groundwater quality between coal seams and wellfield, scenario 3

7.3.6 Three dimensional chloride transport simulation

Since a possible increase of chloride concentration at areas Ia and Ib is identified as the largest threat to water quality, additional 3D transport calculations are made for chloride, to get a better insight into this possible threat. Distribution of the chloride concentrations at the Carboniferous formation is assigned based on the evaluations of ROSNER (2011; see Fig. 18). Chloride concentration in the Aachen/Vaals and the Gulpen/Maastricht formations is set to 50 mg/l. Dispersion is included in the model.

Fig. 58 shows the result for the chloride concentration at the well locations during the calculated period (100 years). From Fig. 58 it follows that only for groundwater extraction north of Benzenrade fault (area Ib) an increase in the chloride concentration is calculated, starting after 30 years and increasing to 1 mg/l, relative to the starting concentration in this well. In the other wells no significant increase of chloride is calculated.

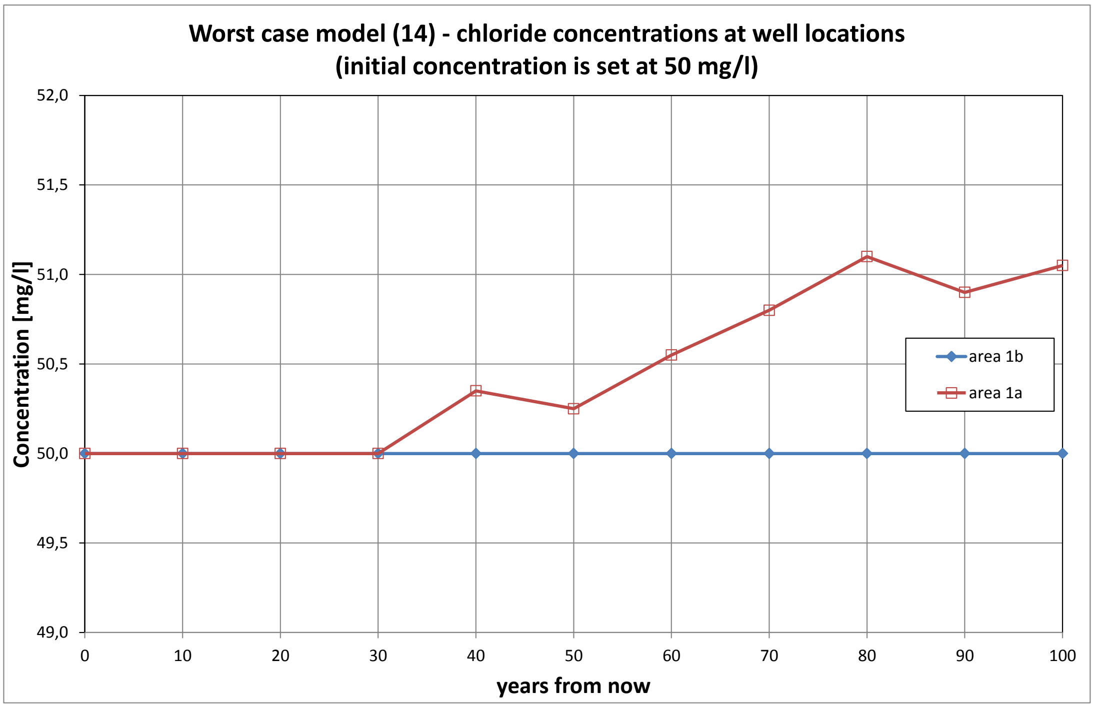

Fig. 58: Calculated chloride concentrations in area Ia and Ib

8 Discussion

8.1 Verification

As shown in Fig. 29, only a few deep observation wells are available in the area of the mining concessions. Therefore it is not possible to calibrate the groundwater model in the same way normal groundwater modelling studies are calibrated. Instead of calibrating, the measurements are compared with the calculated heads of the different scenarios. In the following figures, the calculated heads are shown in the graphs of measured groundwater heads. In these graphs the relevant groundwater extractions are also displayed.

In Fig. 59, Fig. 60 and Fig. 61, the measured heads for wells B60C0860, B60C0839 and B52B0837 are shown. Furthermore, the calculated heads for the Maastricht formation are displayed. For B60C0860 the calculated heads from the different scenarios do not differ much. Filter 3, which is situated in the Maastricht formation, shows a rise in the groundwater level. At the end of the available data the head reaches a height of 42,2 mNAP. In all three wells, the measured heads have not reached the calculated head yet.

The increase in head in the Maastricht formation that has already occurred can not only be caused by rising mine water. In the deep aquifers in southern Limburg, there is a known long-term fluctuation in heads caused by precipitation and evaporation, that is also observed in deeper layers. In these deeper layers the fluctuation is attenuated and temporally shifted relative to the shallower aquifers. Additionally, the groundwater extraction by DSM in Geleen was reduced between 1996 and 2006. The increase in head was therefore larger in that period than before and after that period. Between 2006 and 2014 a gradual increase in heads is observed from 35 mNAP to 41mNAP, which is assumed to be largely caused by rising mine water.

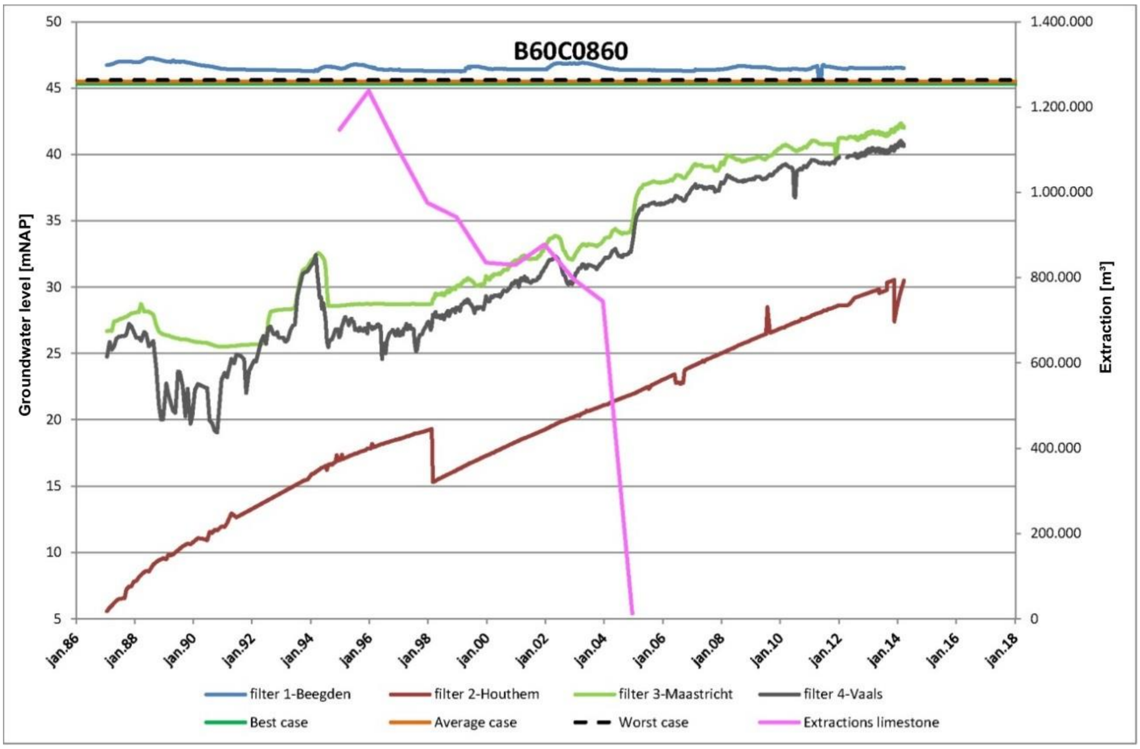

Fig. 59: Measured and calculated heads B60C0860

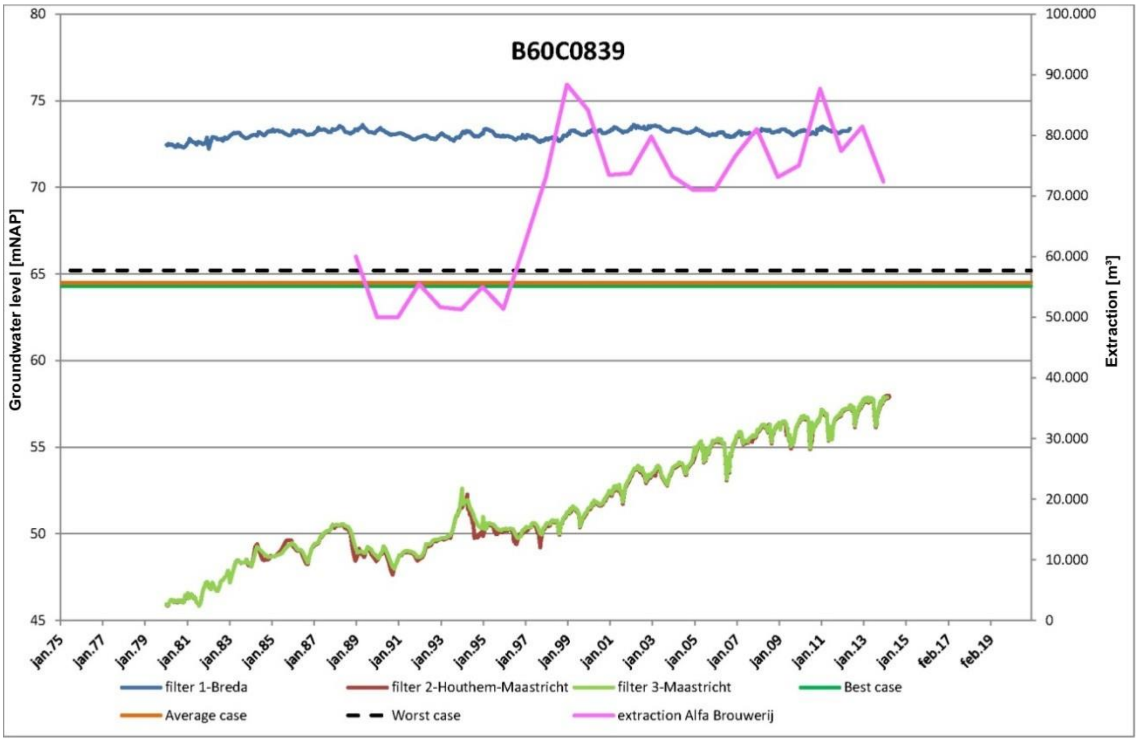

Fig. 60: Measured and calculated heads B60C0839

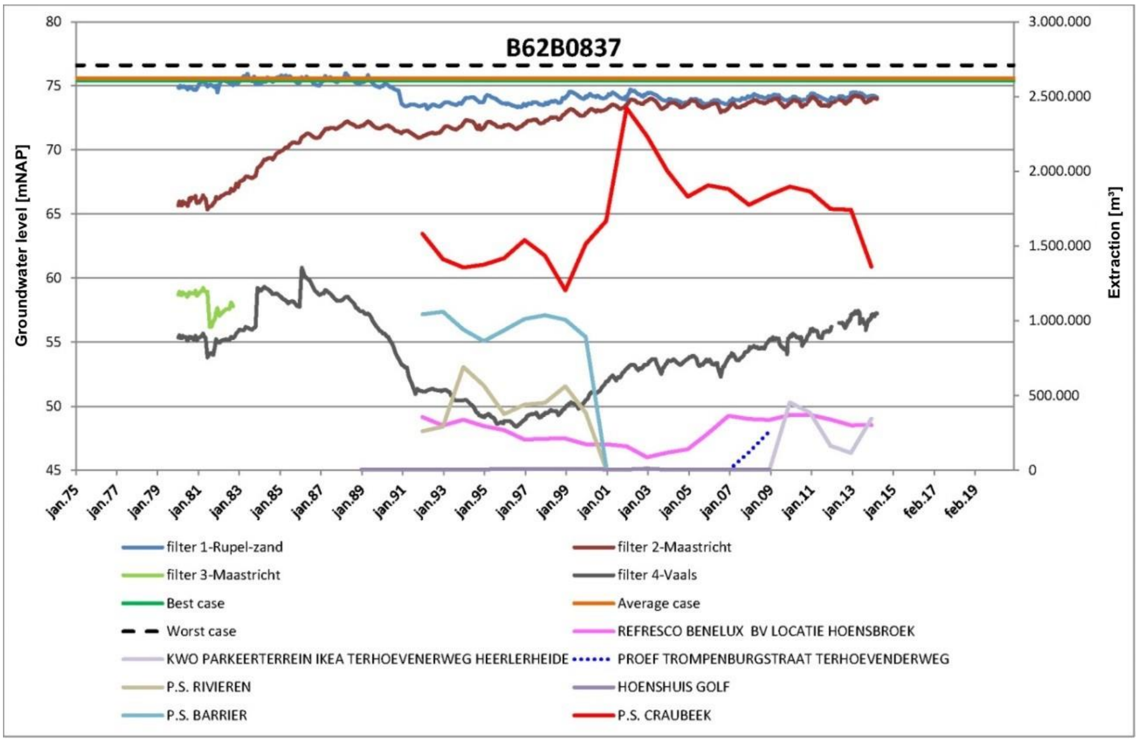

Fig. 61: Measured and calculated heads B62B0837

In the case of the wells -860 and -839, the calculated head lies beneath the phreatic groundwater table. In the end situation, there will still be infiltration in these areas. The head of the Maastricht formation in well -837 has already reached the phreatic groundwater table. The calculated head lies above the phreatic head and the head in the Maastricht formation. It must be considered that the observations in piezometer -837 are strongly influenced by changes in groundwater extraction discharges. In the area around piezometer -837 the drinking water company of Limburg (WML) has ended several groundwater extractions (pumping stations Rivieren and Barrier) and increased the capacity of others (pumping station Craubeek).

In Fig. 62, the heads for observation well -838 are shown. Both the phreatic head and the head of the Maastricht formation lie above the calculated heads.

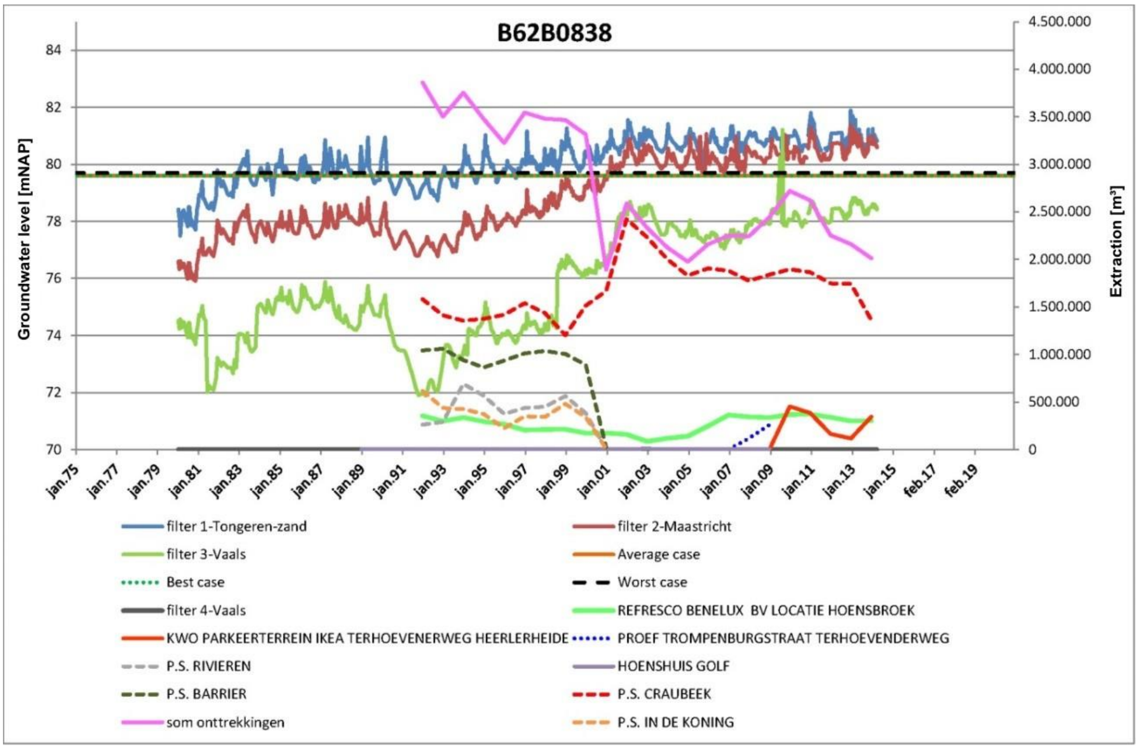

Fig. 62: Measured and calculated heads B62B0838

Fig. 63 shows the rise of the mine water and the measured groundwater levels in the chalk aquifer. The groundwater level in the basement at the beginning of the measurements in 1980 was at least 200 m lower than the groundwater level in the overburden. Nevertheless the rising mine water level constantly reduces the leakage rate from the overburden to the basement. Therefore the speed of the water rise in the monitoring wells -860 and -839, the two far most wells in the northwest, is decreasing.

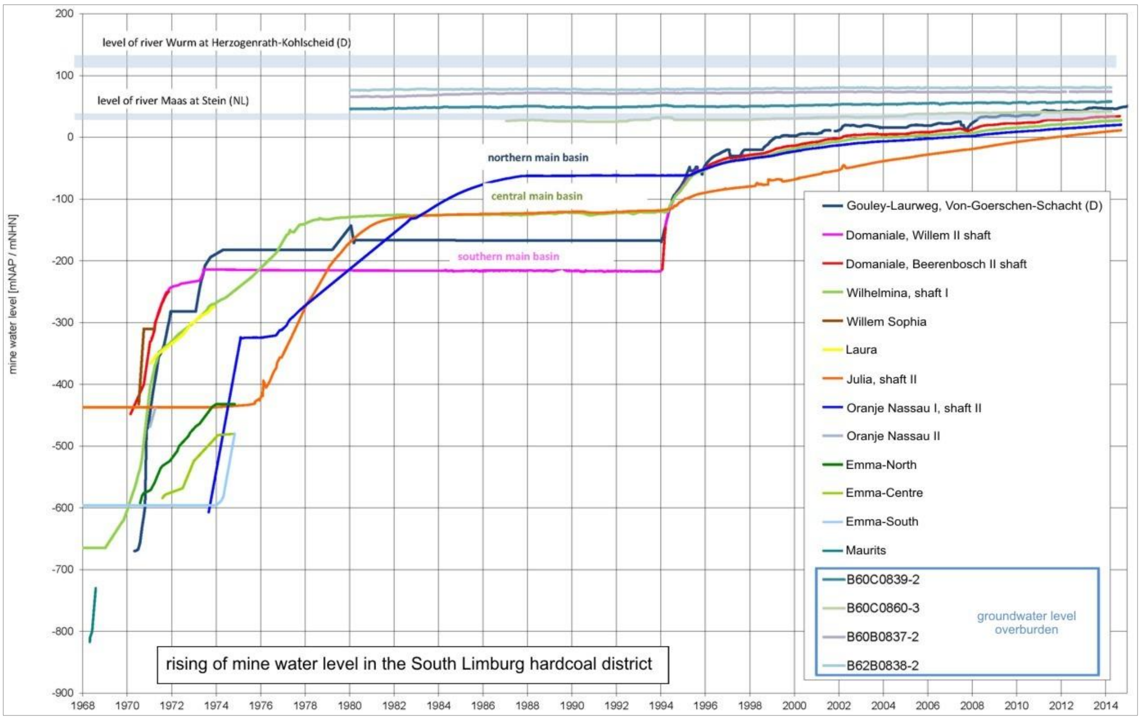

Fig. 63: Rising mine water and groundwater heads in the chalk aquifer

8.2 Plausibility of the parameters and assumptions made

The most important parameters and assumptions made in this modelling study are the following:

- the stage of the river Wurm (eastern model boundary);
- the hydraulic conductivity in the Carboniferous;
- upward flux from the Carboniferous into the overburden;
- boundary conditions at the river Maas (western model boundary).

In the following paragraphs, these issues are being discussed.

8.2.1 The conductivity of the Carboniferous

- Unmined Carboniferous

Different literature shows different values for the hydraulic conductivity of the unmined Carboniferous. In the groundwater model IwanH, which has been developed especially for South Limburg, the Carboniferous has been given a conductivity of $1 \cdot 10^{-3}$ m/d. Values given in literature indicate a conductivity between 10^{-8} and 10^{-10} m/d. To calculate a worst case scenario, the value of $1 \cdot 10^{3}$ m/d is applied to the unmined Carboniferous.

- Mined Carboniferous

There is very little data on the hydraulic conductivity of the mined Carboniferous formation, but based on literature and the pumping tests that were carried out for the mine water project in Heerlen, it is assumed that the conductivity is relatively high. In the model the calculations were carried out with a conductivity of 250 m/d. Sensitivity analysis demonstrated that the hydraulic conductivity of the mined Carboniferous is not a major influencing factor on the heads in the Carboniferous. Lowering the hydraulic conductivity from 250 to 50 m/d results in an increase of the head near the Wurm of around 5 m. It can be concluded that the model results are not sensitive to changes in the hydraulic conductivity of the Carboniferous formation.

- Hydraulic windows

As explained before, in the upper 20 m of the Carboniferous, areas with a large inflow of groundwater from the overburden have been added to the model. These inflows are most likely caused by sandy deposits of the Carboniferous. Because of the sandy properties, these hydraulic windows have been given a conductivity of 5 m/d. Sensitivity analysis showed that the calculated heads in the

Carboniferous and overlying aquifers are relatively insensitive to changes in the hydraulic conductivity of the hydraulic windows. However, the hydraulic conductivity does affect the travel times of mine water to overlying layers. The travel times are significantly shorter in regions where hydraulic windows are found.

8.2.2 Boundary conditions at the river Maas

It is known that there is no connection between the Maurits concession and the Belgian mines on the other side of the river Maas. It is presumed that this barrier is only a few hundred metres wide. This barrier has been translated into the model by adding a horizontal flow barrier on the river Maas in the layers of the Carboniferous. In all the other model layers, the head at the river Maas can fluctuate freely. This leads to an upward flow from the Carboniferous into the overburden. As a result of this upward flow, heads in the overlying aquifers rise, especially in the chalk aquifer.

- Applicability of model results.

Sensitivity analysis performed with the model shows that the results are relatively insensitive to changes in the boundary conditions at the Maas river.

8.2.3 Model structure

In 2009, TNO delivered a geological model of South Limburg called REGIS-II v2.1. This model contains information about the different geological formations, its thickness and presence. REGIS-II v2.1 contains the formations from the youngest Holocene deposits through the Aachen formation. Any deeper formations are not included in REGIS-II v2.1. Based on this model, the groundwater model IBRAHYM has been built.

- Comparing REGIS-II v2.1 and REGIS-II v2.2

Currently TNO is working on an update of REGIS-II, named REGIS-II v.2.2. In this version, recent data from mapping projects will be taken into account when working out the updated geological model. For this project, the available data for South Limburg have been provided. The used groundwater model is based on REGIS-II v2.1, and is not yet updated with the newest data. To oversee the consequences of a new geological model and its impact on the modelling results, the different layers of REGIS-II v2.1 and REGIS-II v2.2 have been compared by TNO in the framework of the study in hand. The comparison and its conclusions are displayed in WITTEVEEN+BOS, 2015).

The comparison shows that there are relevant differences between the two REGIS models. This is partially due to the reinterpretation of data from drillings, even though the relevance of this information is limited for the regional groundwater model. The province of Limburg and the water boards are updating and calibrating the IBRAHYM model.

8.2.4 Accuracy

In 2015 Deltares updated and recalibrated the groundwater model IBRAHYM. It must be underlined, that IBRAHYM is a large, regional groundwater model and is not meant to predict groundwater heads at a small scale. Because of the complex geohydrological system in South Limburg and the steep gradients in the groundwater, deviations will occur. In the report by Deltares these deviations are mentioned. 60 % of the deviations lie between -4,0 and -1,5 m. This means, that in many cases the calculated heads are too low. This should be taken into account by interpreting the modelling results.

In this report the effects of density-flow of groundwater are not taken into account. Saline mine water is (slightly) heavier than fresh water, and this will have an (minor) impact on groundwater heads.

9 Bow-Tie-Analysis

A general overview about the systematic of the Bow-Tie-Analysis is given in chap. 2.3.4. With the results of the investigations in hand two Top Events have been identified regarding the Hazard “rising mine water”:

- change quality of deep groundwater (WG 5.2.4; Fig. 48)
- wetting of stream valleys (WG 5.2.5; Fig. 47)

The single Bow-Ties for these top events are given in Appendix 4 and Appendix 5. In the following the relevant factors of the Bow-Tie are discussed. In the Bow-Tie systematics approach a distinction is made between prevention control measures and recovery control measures. “Prevention control measures” are measures implemented to reduce the probability of occurrence of the so-called “Threats”. “Recovery control measures” are measures that are implemented when the top event (e.g. changing quality of deep groundwater) occurs, and that are designed to reduce the “Consequences” of such an occurrence or mitigate them altogether.

9.1 Top Event: Change quality of deep groundwater (WG 5.2.4)

9.1.1 Threats, Consequences

As a result of rising mine water, especially in the Emma concession, water will flow upwards through layers with a higher conductivity, through hydraulic windows and through badly sealed boreholes and mine shafts. As a result, extracted water by the drinking water company or industry can be influenced.

9.1.2 Prevention Controls

- Pumping of mine water

In practice, the threats can only be mitigated by preventing a further rise of mine water by starting to pump out mine water again. This is a measure that could introduce significant consequences. The pros and cons of restarting the pumping of mine water are discussed in the final integrated risk analysis of this project.

- Locations and discharge of groundwater extraction wells

For new groundwater extractions it is recommended to research the presence of hydraulic windows, and the location and discharge of the proposed wells and let the well configuration be determined by these results.

- Research

The presumed effects of rising mine water are partly based on the modelling performed with the groundwater model IBRAHYM. This model was calibrated using data on groundwater levels, in which no relationship was presumed with rising mine water. It is recommended to recalibrate the model, taking into account the effect of rising mine water. Also, we recommend to install piezometers that are screened in the Carboniferous formation. This data will be valuable input for the future recalibration of the model. Recalculating the effects of rising mine water with the recalibrated model and with the new monitoring data is highly recommended.

9.1.3 Recovery Controls

If groundwater quality is influenced by rising mine water which in turn influences the quality of water extracted by industry or drinking water production companies, then the following recovery control measures can be implemented:

- Monitoring of groundwater quality
- Reducing, stopping or moving groundwater extraction wells
- Regional development planning

In the “Provinciaal Omgevingsplan Limburg”, the province Limburg formulates policy with respect to groundwater extraction and protection, among other methods through the designation of environmental protection zones around wells, or creating drilling free zones. It is recommended to determine whether additional policies should be added with respect to rising mine water.

- Gebiedsdossiers

As a result of the Water Framework Directive and the Groundwater Directive governments in the EU (or in this case the provincial municipality) are required to protect/guarantee the (chemical) quality of groundwater. They are required to implement the necessary measures to prevent or mitigate the introduction of pollutants to groundwater. In that context, the province Limburg drafted gebiedsdossiers for every drinking water and industrial groundwater extraction for human consumption. In these gebiedsdossiers the current situation (the goal, discharge and the depth of the extraction, current water quality and identifiable trends), possible future threats, and measures to mitigate the contamination of groundwater, are described. In these gebiedsdossiers the rise of mine water has not been identified as a possible threat. It is recommended to update the gebiedsdossiers with this extra risk and make agreements on monitoring and potential measures.

9.2 Top Event: wetting of stream valleys (WG 5.2.5)

9.2.1 Threats, Consequences

It cannot be entirely ruled out that locally, in the valleys, the phreatic groundwater levels will rise. Though the calculated increases are relatively small, in regions where the groundwater table lies close to the surface, there may be an increase in water nuisance from high groundwater levels, especially in buildings with unsealed cellars.

9.2.2 Prevention Controls

In order to prevent damage to structures, there are numerous measures that can be implemented such as drainage, pumps, etc. This research does not answer the question which measure should be implemented in which situation. These are highly dependent on local variables, such as the location, characteristics of the subsurface, water management, type of structure etc. These require custom solutions for each individual situation, should groundwater levels rise as a result of rising mine water.

9.2.3 Recovery and Escalation Controls

- 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;

- When an increase of water nuisance occurs, immediate measures could be taken, like drainage, pumps, sealing cellars etc. As stated in chap. 9.2.2. these measures highly depend on local variables, and require custom solutions for each situation.

10 Monitoring

In this report, possible effects of the mine water rise have been investigated. Mine water rise can lead to an upward flow of mine water into overlying aquifers. Most of all this is the matter in the Emma concession and partially in the Oranje Nassau and Hendrik concessions. One of the consequences can be that the composition of extracted water by industries and the drinking water company is affected negatively.

The investigation is based on an analysis of the water system. Hypotheses resulting from this analysis are verified with the groundwater model IBRAHYM.

In groundwater model studies model results are usually calibrated and verified using measured groundwater heads 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 II 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.

Measurements have been carried out on only a few locations in the overlying formations: namely, in the four groundwater monitoring wells of the “Mijnwatermeetnet” and in the area of the groundwater extractions from WML in the Voerendalerveld. Measuring the groundwater head in the Carboniferous is crucial for the following reasons:

- These measurements give insight into the actual situation and the groundwater heads in the future.

- Such a system can obtain information about the structure of the underground and parameters in 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.

- Collecting data about the groundwater quality and the development of the quality is important. Especially in areas where the drinking water supplies might be affected in the future, like Voerendalerveld, but also around industrial groundwater extractions where groundwater is extracted for the production of food. With respect to these extractions measurements can form the basis for an early warning system.

- Delivering accurate information as a basis for other effects like induced seismicity and land movements.

We advise to construct 5 new deep observation wells, all with a filter in the Carboniferous and the above lying aquifers. The locations and motivations for the single wells are presented in Tab. 19. Additionally an observation well near het Loon in Heerlen is advised. This well could provide more information about the measured decline in groundwater head in this area.

North of the Heelerheide 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 present, so there is no actual threat. However, since we do not have any information about the mine water level and groundwater levels in this area, it is adviced to construct an observation well.

Tab. 19: Monitoring - proposed observation wells

Concession	Description	Purpose
Maurits/ Emma	I. next to well B60C0860 II. Eastern boundary Maurits concession III. next to well B60C0839	- Monitoring joint effect of rising mine water in Dutch and Belgian concessions - Delivering information about boundary conditions at the Belgian border - Delivering information about the gradient steep between Emma and Maurits and alongside about the east-west flow of mine water in the Carboniferous - Makes it possible to correlate measured heads in the mine water wells with the since 1980 measured water levels - Delivering information about the presence and workings of hydraulic windows - Delivering data to verify model assumptions and improve the prediction of effects - Measuring the development of the groundwater quality - Alarming by possible threats for the groundwater quality near the groundwater extraction in Schinnen (early warning system)
Emma	IV. Southeastern part Voerendaler-veld (near well B62B0838)	- Monitoring rising heads in the Carboniferous and overlying formations - Detailed information about the top of the Carboniferous - Measuring the development of the groundwater quality - Alarming by possible threats for the groundwater quality near the drinking water extractions (early warning system)
Emma	V. near well B62B0837	- Monitoring rising heads in the Carboniferous and overlying formations - Measuring the development of the groundwater quality - Alarming by possible threats for the groundwater quality near the groundwater extraction Hoensbroek (early warning system)
Oranje Nassau	VI 't Loon Heerlen	- Monitoring heads in the Chalk formation - Confirmation of indications for a huge decline of the head, probably due to loss of groundwater from the Chalk into the Carboniferous.
Oranje Nassau	VII North of Heerlerheide-fault	- Monitoring rising heads in the Carboniferous and overlying formations - Measuring the development of the groundwater quality

11 Summary and conclusions

11.1 Groundwater quality

Hydraulic contact between Carboniferous (containing mine water) and overburden layers can result in the exfiltration of mine water towards these covering layers. Subsequently, water from this covering layer can flow towards nearby shallow aquifers. Hydrogeochemical reactions can occur along flow paths.

The location of these hydraulic contacts in mining areas is important; both in the current situation and in the future, under rising mine water conditions. To identify these contacts and their impact, several soil survey maps have been studied, such as maps with the top level of the Carboniferous, thickness and characteristics of covering layers, contact with shallow aquifers nearby, and characteristics of these shallow aquifers (permeability etc.). Furthermore, information is collected about the situation during mining activities. Were there specific circumstances during mining, which affected this hydraulic contact?

Subsequently, the effect of mine water rise on the occurrence of these contacts is calculated.

The composition of mine water is very different, compared with groundwater in shallow aquifers 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 is mixed with water from shallow aquifers, several hydrochemical reactions will take place. These reactions may cause the dissolution and precipitation of minerals, which in turn, influences groundwater quality. Contamination by arsenic is a particular risk.

The chemical composition of mine water is quite different from the groundwater in the aquifers. Along the flow path between the coal seams and groundwater water quality will change due to different hydrogeochemical processes. To determine the potential risks of rising mine water towards the groundwater aquifers the following analyses were performed:

- First the problem was analysed; possible effects on groundwater quality were identified. Based on the model schematisation the flow path and travel time of mine water was determined.

- Then, 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 “clean” water was calculated for the groundwater layers.

- The third step was to calculate the ratio of mine water and “clean” water, using the 3D transport model MT3DMS.

- The fourth step was to perform a hydrogeochemical simulation of mine water flowing upwards with the PHREEQC programme.

- The final step was to calculate the chloride concentration using the 3D transport model MT3DMS.

Based on the groundwater calculations, sulphate and chloride were 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 near “hydraulic windows”. Where the top of the Carboniferous has not been excavated, travel times are much longer.

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 approximately 150 mg/l.

However, due to mixing it has to be expected that further upward flow and mixing with “chalk” 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 1a there is no increase of chloride calculated. So, for groundwater extractions the consequences seem to be very 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 Heelerheide 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.

It is not expected that the quality of shallow groundwater will be influenced due to rising mine water.

11.2 Wetting

Due to mine water rise, groundwater levels nearby mined areas can also rise. Change in shallow groundwater can lead to wetting.

A groundwater model is used to estimate the effect of mine water rise on phreatic groundwater levels. Assumptions have been made about the amount of water exfiltrating from the Carboniferous towards the shallow aquifers. These assumptions were made upon measurements of mine water level over the past decades, since the mine water pumps stopped. The IwanH-groundwater model was used to calculate the effects. First of all the current situation has been calculated (average situation) and evaluated (depth of groundwater level relative current surface level was calculated). Subsequently, the estimated effect of rise of groundwater levels, due to mine water rise was evaluated.

Due to the rise of mine water, shallow groundwater level will also rise in part of the investigation area. Since groundwater levels are relatively deep in the major part of the study area, the calculated rise will not lead to damage in that area.

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. The rise of shallow groundwater levels will be relatively low: a maximum of 0,1 to 0,25 m is calculated. In general it is not to be expected that this will lead to severe damage to housing, nature or agriculture.

11.3 Bow-Tie-Analysis and monitoring

For mitigating or preventing the effects of mine water rise on groundwater quality, 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 aquifers. 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 into account the effects of rising mine water, when recalculating the protection zones of drinking water extractions

For the handling of potential water nuisance 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 relation between mine water rise - increase of groundwater - damage should be investigated.

- Potential impact areas need to be considered by the planners of building projects, especially in areas where local water nuisance already occurs.

- Proposal for monitoring.

Since there is no information on the groundwater level in the Carboniferous in the major part of our study area, it is advised to install seven deep monitoring wells. The required data will help to improve the model and the predictions of mine water and groundwater rise.

Deventer, 31. August 2016/02. December 2016

Witteveen Bos

Dipl.-Geol. Nancy Sevriens-Visser

Drs. Arie Biesheuvel

ir. Jaap H. Spaans

Aachen, 31. August 2016/02. December 2016

ahu AG

Dr. Michael Denneborg

Aachen, 31. August 2016/02. December 2016

IHS

Dr.-Ing. Michael Heitfeld

Dr. Peter Rosner

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Appendix 1

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working groups
5.2.4 - groundwater quality
5.2.5 - groundwater quantity

Diepteligging van het Carboon oppervlak in het model Na-ijl effecten
Mijnbouw Zuid-Limburg by VAN ROOIJEN ADVIEZEN, 2015

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), 31. August 2016

Diepteligging van het Carboon oppervlak in het model

Na-ijlende gevolgen van de steenkoolwinning in Zuid-Limburg

Als basis van het model voor het project worden de meest recente resultaten van het TNO project REGIS gebruikt. In REGIS zit echter niet de diepteligging van het Carboon oppervlak (TC). Aanvankelijk werd door TNO een aanvullende kaart geleverd voor dit niveau. Deze computerkaart werd onafhankelijk van de REGIS resultaten geconstrueerd en bleek dermate zware problemen te bevatten dat omgezien werd naar een alternatief. Na uitvoerig en tijdrovend overleg tussen de modelbouwers van het project en TNO werd besloten dat de REGIS gegevens van TNO worden gebruikt voor de TC in het gebied zuidwestelijk van de Heerlerheide Breuk en dat uit het reeds bestaande Ibrahym model de TC ten noordoosten van deze breuk wordt gebruikt.

Bij het bestuderen van de diepteligging van de basis Laag 19 van het Ibrahym model (die moet overeenkomen met de Top Carboon) bleken hierin echter zeer grote verschillen te zitten met de toch erg goed gedocumenteerde kaart TC van Patijn uit 1961. Ten noordoosten van de Feldbiss toont Ibrahym duidelijk geringere TC diepten terwijl ten zuidwesten van deze breuk de TC Ibrahym juist aanmerkelijk dieper ligt dan op de kaart Patijn. Afgezien van het daardoor sterk verminderde effect op de verschillen langs de Feldbiss en de mogelijke gevolgen daarvan voor watertransport over de breuk heen, zullen hierdoor ongetwijfeld problemen ontstaan met de dikteverdeling van de verschillende deklagen van het Carboon, zeker daar waar het Carboon omhoog komt tot niet ver onder maaiveld, zoals in het zuidoosten van het modelgebied. Daar ligt bijvoorbeeld, bij boring 62 E-341 (schacht Nulland) TC op +117 m NAP. Op het Carboon ligt ca 15 meter fijn, slibhoudend zand van de Formatie van Tongeren (Laagpakket van Klimmen) en daarop een sterk kleiig, ca 15 meter dik pakket met bruinkoolinschakelingen (Laagpakket van Goudsberg), onder een pleistocene bedekking met Maasgrind en löss van ca 10 meter dik. Als nu, volgens Ibrahym, de TC iets onder +70 m moet liggen, dan moet daar ook een veel dikker Tertiair pakket worden geïnterpreteerd, met bovenin waarschijnlijk een deel van de watervoerende laag van de Formatie van Breda. Ook elders leidt dit tot afwijkingen van de werkelijke opbouw boven het Carboon, waardoor naar alle waarschijnlijkheid de resultaten van het modelonderzoek kunnen worden beïnvloed.

Hieronder enkele resultaten van de vergelijking van TC Ibrahym en de kaart Patijn.

Tussen 1ste NO Hoofdbreuk en Feldbiss

In het noordwesten ligt TC Ibrahym (meer dan) 200 meter te hoog. Zie boringen 24 en 25 (resp. 69 en XLV op kaart Patijn). De fout neemt af naar het zuidoosten. Bij boringen 108 en 219 (XLII en 86) is dit nog een verschil van ca 100 meter. Ter hoogte van Tevenerheide ca 80 meter en bij boring 27 (82) bij Abdissenbosch ligt TC Ibrahym nog 50 meter hoger dan in de boring gevonden en op kaart Patijn aangegeven. Verder naar het zuidoosten neemt het verschil af maar gaan de Ibrahym lijnen dwars door de daar goed gedocumenteerde TC topografie van Patijn, waardoor verschillen weer (zeer plaatselijk) oplopen tot 50 of 60 meter. Bij de Julia ligt TC Ibrahym weer plaatselijk rond 75 meter hoger dan TC Patijn, terwijl daar toch grote zekerheid te vinden is door boringen en schachten Julia (b.v. boring 100 Patijn). Dan verzint Ibrahym rond 700 meter ZO van de schachten Julia ineens een sprong in TC van meer dan 100 meter. Het is niet duidelijk waarop dit is gebaseerd. Daardoor komt verder naar het zuidoosten de TC Ibrahym juist beduidend dieper dan bij Patijn en lopen de lijnen ook vaak haaks op elkaar.

Tussen Feldbiss en Heerlerheide Breuk

In het noordwesten, bij Wintraak, legt Ibrahym de TC duidelijk te diep. Verschillen met Patijn tot 50 meter zijn de norm. Vergelijk boringen 60C-294 (64 bij Patijn) en 60D-4 (84 Patijn). Ibrahym TC ligt resp. 50 en 55 meter te diep. Interessant is dan wel de Duitse hoek bij Hillensberg, waar Ibrahym de grens volgt met een sprong omhoog. Hierdoor komen de verschillen met Patijn daar bijna te vervallen, maar de dieptelijnen van Ibrahym kruisen die van Patijn veelal. Dan verder naar het zuidoosten, het gebied Douvergenhout, Oirsbeek en Amstenrade. TC Ibrahym weer aantoonbaar te diep. Verschil met Patijn weer rond 50 meter. Vergelijk boringen 60D-39, 40, 42, 65, 67, 68, 164 en 169 (resp. LI, 66, XL, 49, 65, XIX, IX en XXI bij Patijn). Een grillige wirwar van dieptelijnen TC van Ibrahym volgt in het gebied Treebeek – Brunssum, met TC Ibrahym vaak 50 - 70 meter dieper dan de in boringen en schachten aangetoonde werkelijkheid. Het is volslagen duister waarop de kennelijk computergestuurde Ibrahym lijnen zijn gebaseerd. Ook verder naar het zuidoosten, waar het Carboon oppervlak omhoog komt tot boven NAP, ligt TC Ibrahym tot wel 80 meter dieper dan bij Patijn, zoals bij coördinaat 197.000 - 322.500 in Heerlen (-70 en +10 m) en bij 199.350 – 322.700 in Schaesberg (-40 en +40m). En dit verschil blijft onverdroten doorlopen verder zuidoostelijk. Zo ligt TC Ibrahym bij de schachten SM Wilhelmina nog steeds 50 meter dieper dan bij Patijn (+10 i.p.v. +60m) en 60 meter dieper bij Neu Prick (+80 i.p.v. +140m. Opvallend is ook dat TC Ibrahym de lijnen soms ongestoord door goed gedocumenteerde breukjes aan Top Carboon laat lopen.

Klimmen, 28 juli 2015

P. van Rooijen.

Appendix 2

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working groups
5.2.4 - groundwater quality
5.2.5 - groundwater quantity

Comments on REGIS-II v2.1 and REGIS-II v2.2
by VAN ROOIJEN ADVIEZEN, 2015

by

Projectgroup
"Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg"
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on behalf of
Ministerie van Economische Zaken - The Netherlands

Aachen (D), Deventer (NL), 31. August 2016

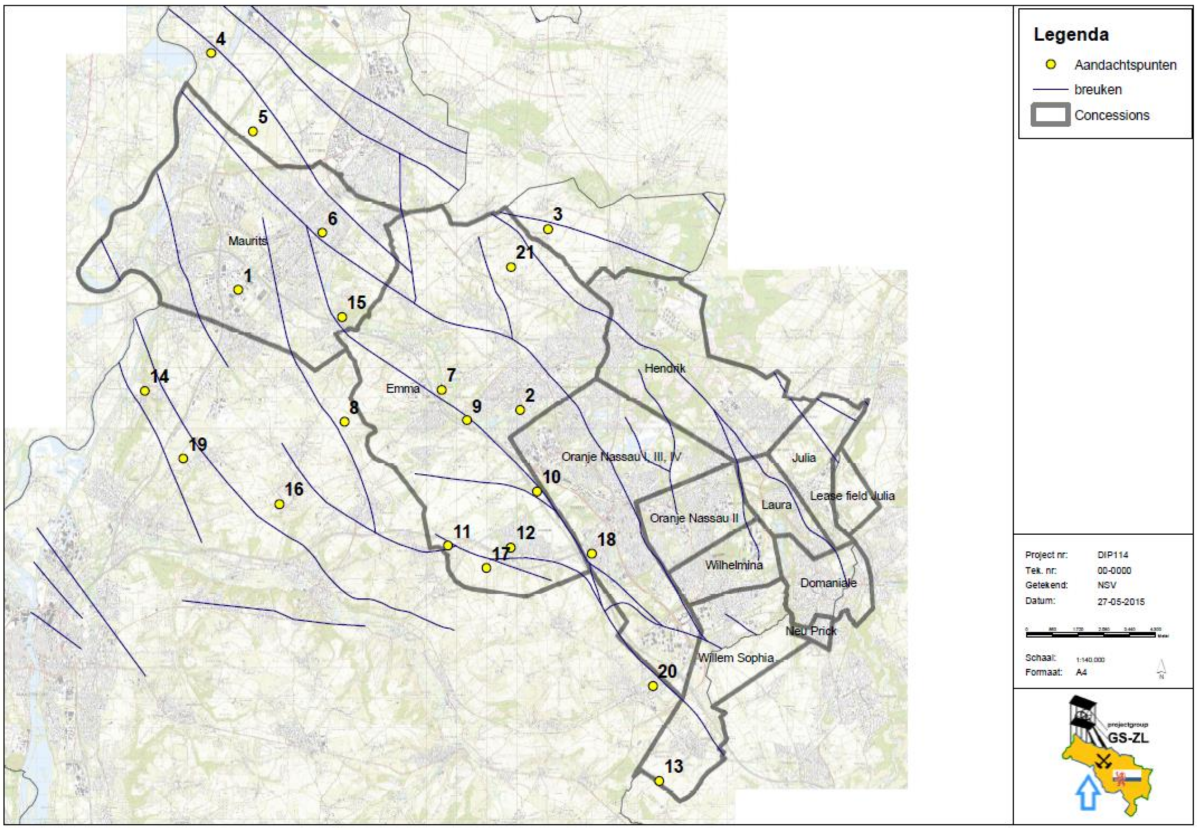
Bevindingen bij de geologische aandachtspunten,

Model na-ijl effecten Mijnbouw Zuid-Limburg

Bij de opbouw van een grondwater stromingsmodel voor het inschatten van de na-ijlende effecten van de Zuid-Limburgse steenkoolwinning werd door de modelbouwers een aantal onduidelijkheden gevonden in de aangeleverde basiskaarten. Deze werden als aandachtspunten geregistreerd en door Van Rooijen Adviezen nader bekeken en geëvalueerd.

Als basis voor het model wordt ten noordoosten van de Heerlerheide Breuk de kaart Ibrahym genomen voor de Top Carboon en voor het gebied ten zuidwesten van deze breuk vormt een TNO kaart de basis voor Top Carboon. Voor de deklagen van het Carboon wordt REGIS als uitgangspunt genomen. Bij de aandachtspunten gaat het met name om grotere dikteverschillen tussen eerder door TNO gemaakte kaarten (REGIS 2.1.) en de meest recente constructie (REGIS 2.2.).

In het algemeen moet worden opgemerkt dat het qua hydrologie weinig zal uitmaken of een sedimentinterval tot de Formatie van Maastricht of tot de Formatie van Houthem wordt gerekend. Het gaat wat doorlatendheid betreft immers slechts om de bovenste zone van het gehele chalk pakket. Aan alles wat zich van de chalk op grotere diepte bevindt onder het chalk oppervlak moet een (zeer) geringe doorlatendheid worden toegeschreven. Bij dikteverschillen kan het van belang zijn om welk laagpakket het binnen een formatie gaat. Lokaal kan bijvoorbeeld de bovenste zone van de Formatie van Tongeren, het vaak zeer kleiig ontwikkelde laagpakket van Goudsberg, dermate afsluitend zijn dat zich daaronder in het zandige laagpakket van Klimmen een eigen grondwaterstand vormt die sterk afwijkt van de freatische waterstand maar ook van de waterstand in het Carboon (b.v. in gebied Heerlen-Kerkrade).



Punt 1

Hier ligt een aantal diepe waterputten van DSM. Het gaat hier vooral om dikten Tongeren (de Goudsberg laag) en Maastricht. Het laagpakket van Goudsberg is hier waarschijnlijk slechts ca 5 meter dik. Verwarrend is de afhankelijkheid van oude lithologische beschrijvingen van de boringen. Het pakket kleiig zand en zandige klei wordt per boring anders beschreven zodat men er alle kanten mee op kan, en ook is gegaan kennelijk. Het is een combinatie van diverse lagen van de Formatie van Rupel en de F. van Tongeren. Ook in de oorspronkelijke REGIS kartering leidde dit eerst tot enorme verschillen in dikte Goudsberg. Lijkt dus van weinig belang, mits de gemodelleerde doorlatendheden geen grote verschillen laten zien. Maastricht is hier dikker dan in de omgeving; Houthem juist dunner. Gaat hier dus (grotendeels?) om stratigrafische toewijzing van de chalk (zie boven). Het totale pakket chalk is hier waarschijnlijk rond 110 meter dik, waarvan ca 40 m Houthem. Waarom hier dan relatief dunne Houthem laag is gegeven in REGIS 2.2. is onduidelijk, maar hydrologisch dus minder van belang.

Punt 2

Hier ligt boring 60D-655 met een pakket Maastricht en Vaals samen van 100 meter. Kimpe (1961) verdeelt dit onder in ruim 35 m Maastricht en 65 m Vaals.

TNO ziet hierin 80 m Maastricht en 20 m Vaals omdat de beschrijving veel “mergel” vermeldt. Maar deze is vanaf 37 m onder de top Maastricht al kleiig en vermengd met glauconiet zand, zodat de interpretatie van Kimpe verantwoord is. Harde banken komen ook in Vaals voor. REGIS 2.1. geeft Maastricht een dikte van 80 m en 2.2. insgelijks. Maar in beide gevallen is de dikte duidelijk groter dan in de omgeving. Bij Vaals laat REGIS juist het omgekeerde zien, met voor het gebied anomaal geringe dikten. Duidelijk is dat zowel 2.1. als 2.2. onverantwoord zijn hier en een revisie nodig is overeenkomstig de interpretatie uit 1961.

Punt 3

Dit punt ligt ca 150 meter ZW van de diepboring 60D-1039 uit 1993. Hier is Goudsberg 7½ m dik en Maastricht ruim 30 m. Wezenlijke verschillen lijken hier niet te bestaan tussen REGIS 2.1. en 2.2. Hooguit een miniem verschil in dikte Tongeren zand 1, maar dit is niet te baseren op de lithologie van boring 1039 en dus slechts een onbetekenende computer interpretatie. De aanleiding tot het geïnterpreteerde verschil van meer dan 10 meter in kaart verschil Tongeren is onduidelijk, niet te baseren op de lithologische beschrijving van boring 1039 en dus van geen belang.

Punt 4

Hier is naar mijn weten geen boring. Als er ook geen seismiek over dit punt loopt is deze situatie heel vreemd. Terwijl ca 1250 m zuidelijk van dit punt nog 80 m Maastricht en geen Houthem aanwezig is zou hier, tegen de Geleen Breuk, juist geen Maastricht meer zijn en wel ca 50 m Houthem. Lijkt geen kwestie van stratigrafische indeling. Van groter hydrologisch belang is dat NW van dit punt 4 bij de Maas geen Houthem meer zou zijn, maar ook geen Maastricht. In ’t geheel geen chalk dus meer (REGIS 2.2.)!?? Is er in aangrenzend België soms een boring? Vraag voor TNO.

Punt 5

Maastricht of Houthem. De situatie is hier inderdaad vreemd. Er liggen drie oude diepboringen in deze tektonische schol op een lijn NW-ZO. Dicht bij de Maas, 60C-25, heeft ca 80 m kalksteen van -320 tot -397. 2250 meter verder ZO ligt 60C-83 met 150 m kalksteen van -179 tot -329 m en nog 1900 m verder ZO ligt boring 60C-162 met ca 55 m kalksteen van ca -210 tot -265 m NAP. Al is de lithologische beschrijving vaak vaag, ook het verloop van de ondiepe bruinkoolhoudende laag Ville wijst op een gelijkmatige daling van de lagen naar het NW. De conclusie lijkt hier voor de hand te liggen dat bij punt 5, dat min of meer overeenkomt met boring 60C-83, een oude topografische bult zit in het erosievlak top chalk. Voorheen werd de chalk hier voor het overgrote deel toegeschreven aan het Paleoceen, Houthem dus. Maar TNO ziet dit nu kennelijk als Maastricht. De veranderde toewijzing maakt hier het verschil. Hydrologisch van weinig of geen belang dus (vergelijk REGIS profiel Li-8-zuid).

Punt 6

Moet op dezelfde schol liggen als punten 4 en 5. Hier geen boring bekend. Lijkt dus geheel een computer interpretatie. Ca 2500 m ZO ligt nog boring 60C-323 in deze schol, met chalk van -220 tot -300 m. Toegewezen aan Maastricht eerder. Nu hier 60-70 m Maastricht en 10-20 m Houthem. Kan dus nog goed zijn. Maar de computer geeft in 2.1. en 2.2. een verschillend diepteverloop tussen boringen 60C-323 en 162 (zie punt 5), waardoor hier verschil ontstaat. Van weinig belang. Aanhouden 2.2. oké.

Punt 7

Dikte Maastricht hier in REGIS 2.1. zeer plaatselijk ca 30 m geringer dan in omgeving. In 2.2. is deze anomalie verdwenen. Bij Vaals zijn deze verschillen juist omgekeerd. Ter plaatse van punt 7 ligt boring 60D-443 met 60 m Maastricht en ruim 55 m Vaals. Dat komt redelijk overeen met 2.2., zodat 2.1. als foutief moet worden gezien. Aanhouden 2.2. dus oké.

Punt 8

In 2.2. is hier Vaals bijna 30 m dunner, maar Maastricht juist meer dan 20 m dikker dan in 2.1. Het dichtst in de nabijheid ligt boring 417, ca 500 m NW van punt 8, met kalksteen van -35 tot -105 m en daaronder bijna 60 m Vaals tot aan het Carboon oppervlak (ca -165 m). De dikte Maastricht in 2.1. is duidelijk te gering en in 2.2. iets aan de dikke kant. Versie 2.2. is voor Maastricht dus iets beter. Voor Vaals is versie 2.1. duidelijk beter (dikte bijna 60 m) dan 2.2. (ruim 30 m). Dit is te verklaren door de afwezigheid van Vaals ca 1200 m naar het ONO (boring 418), waar het kalksteen pakket direct op het Carboon ligt. De computer heeft zich daardoor mogelijk teveel laten beïnvloeden.

Punt 9

Vergelijkbaar met punt 7, alhoewel aan de andere (ZW) kant van de Benzenrade Breuk. Maastricht in 2.1. meer dan 100 m dik. In 2.2. ruim 70 m. Vaals is in 2.1. minder dan 10 m en in 2.2. tussen 40 en 50 m dik. Dichtbij ligt boring 60D-650 met ca 55 m Maastricht en ruim 60 m Vaals. Een nog wat dikker Vaals en minder dik Maastricht zou hier beter zijn, maar 2.1. was abnormaal afwijkend. Ook hier aanhouden 2.2. dus beter.

Punt 10

Ingeknepen tussen Benzenrade Breuk en Revieren Breuk maakt de computer hier vreemde bokkensprongen die niet kunnen worden onderbouwd met boorgegevens. Bij Kasteel Revieren is het pakket Maastricht + Vaals tezamen rond 150 m dik, misschien iets meer. Hiervan zal Maastricht 70 à 75 m dik zijn. REGIS 2.1. maakt dit zeker 10 m dikker maar 2.2. is met een dikte van 30-40 m duidelijk anomaal, en het verschil dus ook. Voor Vaals hanteert 2.1. een dikte van 70 à 80 m (?), maar 2.2. meer dan 100 m, met een navenant verschil van meer dan 20 meter. Hier is REGIS 2.1. duidelijk te verkiezen boven 2.2. en dit punt tussen de breuken behoeft aanpassing.

Punt 11

Het probleem is hier het verloop van de Kunrade Breuk. De computer weet hier geen weg mee. Mede op grond van een aantal nieuwe boringen werd door Van Rooijen al een herinterpretatie gemaakt van het verloop van deze breuk, waarbij de bochtige aansluiting van voorheen onderscheiden breukdelen bij punt 11 niet nodig is en in plaats daarvan een “en echelon” verloop van de breukdelen ongeveer parallel aan elkaar werd voorgesteld. De WZW-ONO verbinding net door de kerk van Klimmen komt dan te vervallen en in plaats daarvan lopen de laaggrenzen in zuidoostelijke richting relatief sterk omhoog tussen de breukdelen. Eerder werd dit met TNO besproken bij de REGIS kartering. Bij punt 11 is basis Tongeren aannemelijk bij ca +90 m, basis Maastricht bij +10 à +20 m. Aken is (waarschijnlijk) afwezig. Top Carboon (basis Vaals) is moeilijk vast te stellen. Patijn geeft hier, bij gebrek aan gegevens, geen duidelijkheid en de Kunrade Breuk lijkt in ’t geheel geen effect op Top Carboon te hebben in de kaart uit 1961. Aannemelijk is dat het Carboon oppervlak ook sterk omhoog loopt naar het ZO tussen de breukdelen hier en dat bij punt 11 een Top Carboon verwacht kan worden van rond -70 m of hoger. De dikte van Vaals komt in dat geval in de orde van 80 meter en Maastricht zou 70 à 80 m dik zijn. Maar veel is hier nog speculatief zonder aanvullend onderzoek.

Punt 12

Het gaat hier, bij Hoeve Lindelauf te Voerendaal, weer om de verschillen in dikten Vaals en Maastricht tussen REGIS 2.1. en 2.2. Niet ver af ligt boring 62B391, maar deze is summier en onduidelijk beschreven. Omdat het effect van de Kunrade Breuk ook hier onduidelijk is blijft de geologische situatie nogal speculatief. De waarschijnlijke dikten zijn voor zowel Maastricht als Vaals tussen 55 en 60 meter. De interpretatie REGIS 2.1. moet dan ook worden verworpen en 2.2. kan worden aangehouden.

Punt 13

Een verschil in dikte Maastricht van 20-30 m langs de grens met Duitsland. REGIS 2.2. laat hier Maastricht verdwijnen. Maar er is zeker nog (veel) kalksteen en ook verder zuidelijk, zeker op de grotere hoogten. Dat wordt dan Gulpen genoemd, maar het onderscheid is moeilijk. Hier net in de faciësovergang van Gulpen in het zuidwesten naar Vaals verder noordoostelijk, waardoor dikteverhoudingen gecompliceerd worden. De Maastricht dikte van 40-50 m ZO van punt 13 (2.1.) is niet te onderbouwen en dat geldt dus ook voor het verschil in dikte. Beter om hier het totale kalksteen pakket te modelleren voor hydrologisch onderzoek.

Punt 14

Dikten Vaals 80-90 m in 2.1. en 50-60 m in 2.2. Dikten Aken hier 0 m (2.1.) en rond 30 m (2.2.). Kennelijk is het onderste deel van het hier ruim 80 m dikke pakket zand met kalksteeninschakelingen nu door TNO aan Aken toegewezen i.p.v. aan Vaals. Kimpe (1961) beschouwt het pakket van de kalksteeninschakeling en het onderliggende groene, glauconiethoudende zand als Vaals (boring 504, Geulle, ca 500 m NNW van punt 14) en er is weinig reden om daarvan af te wijken. De herziening van REGIS 2.2. is dus discutabel, maar mag voor het hydrologisch model geen verschil maken.

Punt 15

Bij Spaubeek. Ca 400 meter NNO van boring 60C-373. De Benzenrade Breuk ligt op de kaart Kimpe (1961) bijna 300 m ten noordoosten van dit punt en ook aan maaiveld zal de breuk waarschijnlijk nog NO van dit punt liggen i.p.v. zuidwestelijk daarvan zoals in REGIS aangegeven. Hoe dan ook lijkt deze breuk hier weinig of geen effect meer te hebben. Het probleem ligt hier blijkbaar in de dikte Vaals. In REGIS 2.1. is deze 10 à 20 m, in 2.2. net boven 40 m. Maar bij gebrek aan boorgegevens lijkt een dikte van 30 m of iets meer hier en verder noordwestelijk een redelijke aanname. Het verschil bij punt 15, dat waarschijnlijk ook ZW van de breuk ligt, lijkt dus niet relevant. Wel zijn er aanwijzingen dat de zone waarin de kalksteen direct op Carboon ligt, rond 2½ km ZO van punt 15, (aanmerkelijk) groter is dan in de kaart dikte Vaals 2.2. is aangegeven. De zone strekt zich mogelijk uit van boring 418 via boring 390 (?) tot bij de boring 60C-839, die destijds juist werd gemaakt i.v.m. de mogelijkheid van het omhoog komen van mijnwater naar het dekterrein, maar rond 10 meter boven het Carboonoppervlak moest worden gestopt.

Punt 16

Vaals is hier kennelijk in 2.2. tussen 10 en 20 meter dikker dan in 2.1. Maar Aken komt hier niet voor en bij Maastricht is geen verschil tussen 2.1. en 2.2. Basis chalk hier rond -75 m (klopt in 2.2. en 2.1.). Dikte Vaals in 2.2. ca 60 m, in 2.1. rond 47 m. Basis Vaals ca -137 m in kaart Top Carboon TNO. Klopt dus aardig met 2.2. Waarschijnlijk eerdere Top Carboon kaart afwijkend. REGIS 2.2. dus aanhouden.

Punt 17

Het gaat hier kennelijk om de dikte Vaals. Omdat de Top Carboon hier onzeker is valt, met een basis kalksteen van rond +60 m, slechts een globale uitspraak te doen over de dikte van Vaals. Bij een aangenomen basis Vaals van -50 m zou dat 110 m moeten zijn. Dat komt beter overeen met REGIS 2.2., maar groot is het verschil met 2.1. niet.

Punt 18

Geen Maastricht en wel of geen Vaals. Daar draait het hier om. Punt 18 ligt 500 m ZZW van boring 62B-351, waar geen Maastricht werd gevonden maar wel een dunne laag Vaals (ca 7 meter). Maar ca 1250 m NNO van punt 18 en ruim 750 m NNO van boring 351 liggen de boringen ’t Loon, met iets meer dan 20 meter Maastricht en geen Vaals. Nog eens 650 m verder NNO ligt boring 279, met meer dan 20 m (mogelijk rond 27 m ?) Maastricht en daar is een Vaals dikte van rond 15 m aannemelijk. Ook de boring HLN2, op het ABP terrein Heerlen, heeft 15 m Maastricht terwijl in REGIS 2.2. nog 0-10 m dikte wordt gegeven. Kennelijk is de boring bij Hoeve Terworm wel meegenomen in REGIS 2.2. maar de boringen ’t Loon en HLN2 niet. Dit behoeft aanpassing. Ook de opwaartse boring (820) vanuit het mijngebouw, 350 m WNW van boringen ’t Loon, geeft overigens wel 20 m Maastricht maar geen Vaals. Bij de voormalige Vroedvrouwenschool (Park Imstenrade) ligt boring 439 waar het Carboon direct wordt overdekt door Tongeren. Hier zit dus een gat in Vaals, maar 2.2. geeft hier nog 10-20 m van deze formatie.

Punt 19

Dikten Vaals ruim 70 m (2.1.) en 40-50 m (2.2.). Dikten Aken 0-10 m (2.1.) en bijna 20 m (2.2.). Het probleem hier bij Vliek, Ulestraten, tussen de Geulle Breuk en het verlengde van de Schin op Geul Breuk, lijkt te liggen in de snelle omslag van het dikteverschil in Aken tussen REGIS 2.1. en 2.2. Maar in deze schol nam de dikte Aken in 2.1. van ZO naar NW af tot 0 m bij de A2 en neemt die in deze richting juist toe in 2.2. Vandaar dat het verschil bij punt 19 snel oploopt. Net als bij punt 14 gaat de diktetoename hier van ZO naar NW gepaard met de dikteafname van Vaals in de nieuwe TNO interpretatie. Ook hier mag dit hydrologisch van weinig of geen belang zijn.

Punt 20

Een geïsoleerd voorkomen van Aken in dikte boven 50 meter. Ten westen, noordwesten en dichtbij ten zuiden zijn dikten van net boven 30 m aanwezig. Ten noordoosten ligt een systeem van breuken. Weinig houvast hier. Maar ca 200 m ZZO van punt 20 ligt boring 62B-492, met Vaals tot rond 77 m diepte (= ca +65m). Daaronder ligt een pakket grijze zandige klei en kleiig zand tot 142 m diepte (= 0 m NAP) dat als Aken kan worden genomen o.a. op grond van paleontologisch onderzoek. Dikte zou dan inderdaad 65 m bedragen. Het probleem is echter dat de Top Carboon in deze boorbeschrijving niet is aangegeven en het overigens wat speculatieve Carboon oppervlak in de kaart Patijn rond +25 m zou moeten liggen. Daarmee zou de Aken dikte worden gereduceerd tot rond 40 m en de beschrijving van dit traject in de boring kunnen slaan op de verweerde Carboonlaag i.p.v. op Aken. De sterk afwijkende dikte in REGIS 2.2. zou daarmee deels komen te vervallen, maar onzekerheid blijft.

Punt 21

Het zal hier gaan om de Formatie van Maastricht. Maar ook aan de toewijzing aan Maastricht versus Houthem. In dit gebied komt ca 20 à 30 meter kalksteen voor die door Kimpe (1961) grotendeels wordt geïnterpreteerd als Maastricht. Ook TNO zag hierin vooral Maastricht (profiel Li-8-zuid). Ten westen van de nabijgelegen NNW-ZZO lopende “aftakking” van de Heerlerheide Breuk interpreteerde TNO de kalksteen echter ineens als Houthem, terwijl het dikteverloop van het kalksteenpakket en het toch redelijk consistente verloop in diepteligging van het pakket hier geen aanleiding voor lijken te geven. Nieuwere boringen zijn hier niet bekend. Ter plaatse van punt 21 is er dan ook geen aanwijzing voor het “hoog” in Bottom Houthem (en ook niet in Bottom Tongeren!) en de wulpse kronkelingen in de dieptelijnen van Bottom Houthem. Ook is er geen grond voor het gat in Maastricht ca 1500 meter ZZO van punt 21 (hier precies boring 60D-68!) waar Houthem juist 20-30 m dik zou zijn volgens REGIS 2.2. De diktetoewijzingen maken de zaak in dit gebied zo gecompliceerd, terwijl het kalksteenpakket eigenlijk juist redelijk gelijkmatig naar het noordwesten in diepte toeneemt. Voor model van belang dus slechts Bottom Maastricht en Bottom Tongeren.

Conclusie

Concluderend kan worden opgemerkt dat REGIS 2.2. een aantal verbeteringen bevat t.o.v. 2.1. Maar op een aantal plaatsen is ook revisie van 2.2. noodzakelijk. De verschillen mogen dan soms voor hydrologisch onderzoek van minder belang zijn, maar hebben stratigrafisch en structureel wel degelijk betekenis.

Aanvullende opmerkingen

Naast de boven besproken aandachtspunten kunnen de volgende opmerkingen worden gemaakt:

Rond coörd. 192.500-328.000 valt, net ten zuiden van de Heerlerheide Breuk, de anomaal grote dikte van Maastricht op in REGIS 2.2. en in 2.1. Geen verschil van betekenis dus tussen de beide versies, maar deze dikteanomalie is discutabel en waarschijnlijk ontleend aan de boorinformatie van boring 60D-287. De boorbeschrijving geeft “mergel” aan van 92-195 m diepte. Maar mergel werd in deze oude steenkoolboringen als beschrijving vaak gebruikt voor wat verhard kleiig zand. Beter verantwoord lijkt het dan ook om hierin Kimpe (1961) te volgen en Maastricht te interpreteren van 92-173 meter diepte.

Rond coörd. 183.500-332.000 is Maastricht anomaal dun in zowel 2.1. als 2.2. Ruim 500 m naar het NNW ligt boring 60C-190, ook nog in de zone met geringe Maastricht dikte. Van de ca 80 m beschreven kalksteen werd door Kimpe slechts de onderste 30 meter als Maastricht onderscheiden. Het pakket daarboven werd gezien als Houthem. Maar Kimpe laat de dikte Maastricht (geleidelijk) teruglopen tot 0 meter verder noordwestelijk bij de Maas, en toenemen ten koste van Houthem naar het zuidoosten, in tegenstelling tot de REGIS interpretatie, waardoor deze anomalie van Maastricht dikte ontstaat. En waar de dikte Maastricht gering is laat REGIS (2.1. en 2.2.) de dikte Houthem anomaal groot zijn. Het gaat hier dus weer om een discutabele stratigrafische toewijzing van het kalksteenpakket en voor het model zou dit van minder belang hoeven te zijn, zoals ook bij andere aandachtspunten al is opgemerkt.

Bij coörd. 187.300-332.700 ligt een dikteanomalie voor Tongeren. Maar ook ligt hier boring 60C-206, met minimaal een Tongeren dikte van -293 tot -378 m, alhoewel Kimpe hier een dikte van meer dan 200 m aangeeft. Maar de Tongeren dikte is 800 m ten noorden van boring 206 zeker niet minder. Hier ligt boring 165, met minimaal Tongeren van -320 tot -420 m (Kimpe: 245 m dik) maar daar geeft REGIS 2.2. een dikte van 60 m aan. Kortom, deze anomalie is volledig ongefundeerd en de stratigrafie is hier nog verre van duidelijk.

De breuken zijn op de verschillende kaarten nog niet gelijk aangegeven. In REGIS 2.2. kaarten Bottom Vaals en Maastricht wordt in dieptelijnen een breukje gesuggereerd dat van rond coörd. 187.500-322.500 naar het NNW loopt en daar aansluit op de ingetekende breuk. Dit is de interpretatie die door Van Rooijen destijds tijdens het REGIS onderzoek aan TNO werd voorgelegd op grond van een kartering in dit gebied van Top Kalksteen. De breuk moet dan wel ook in de 2.2. kaarten worden ingetekend i.p.v. het oude breukverloop en eveneens op kaarten van de andere niveaus moeten worden aangepast. In de nieuwste kaart Bottom Tongeren is deze aanpassing overigens al duidelijk verwerkt.

Bij aandachtspunt 11 is de discussie over het verloop van de Kunrade Breuk al aan de orde geweest. De onnodige, bochtige breukverbinding door de kerk van Klimmen is op de meeste aangeleverde kaarten nog te zien, maar op de nieuwste kaart Bottom Tongeren 2.2. correct verlaten. Verdere aandacht hiervoor is nog nodig.

Rond de Julia worden kronkelingen in de kaart Bottom Tongeren getoond die wel erg afwijken van de hier goed gefundeerde kaart Patijn (1961). Ook grote verschillen hier met de meest recente TNO kaart Top Carboon, terwijl Tongeren hier toch direct op Carboon ligt.

Bij coörd. 194.300-322.450 valt de Top Carboon (laatste kaart TNO) net ten noordoosten van de Benzenrade Breuk weg tot -100 m. Hier ligt boring Hoeve Terworm, met Top Carboon op -16 m. Deze boring is kennelijk nog niet meegenomen in kaart TC maar wel in de REGIS kaart Bottom Tongeren. Ook ca 2250 m NO van deze locatie zit tegen de Heerlerheide Breuk een onverantwoord gat in de TC kaart met een diepte van rond -100 m.

Klimmen, 15 augustus 2015.

Drs. P. van Rooijen.

Appendix 3

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working groups
5.2.4 - groundwater quality
5.2.5 - groundwater quantity

Modell scenarios - calculated heads for worst case
and best case scenarios

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), 31. August 2016

(Rev. a: 02. December 2016)

Appendix 3: Model scenarios - calculated heads for worst case and best case scenarios

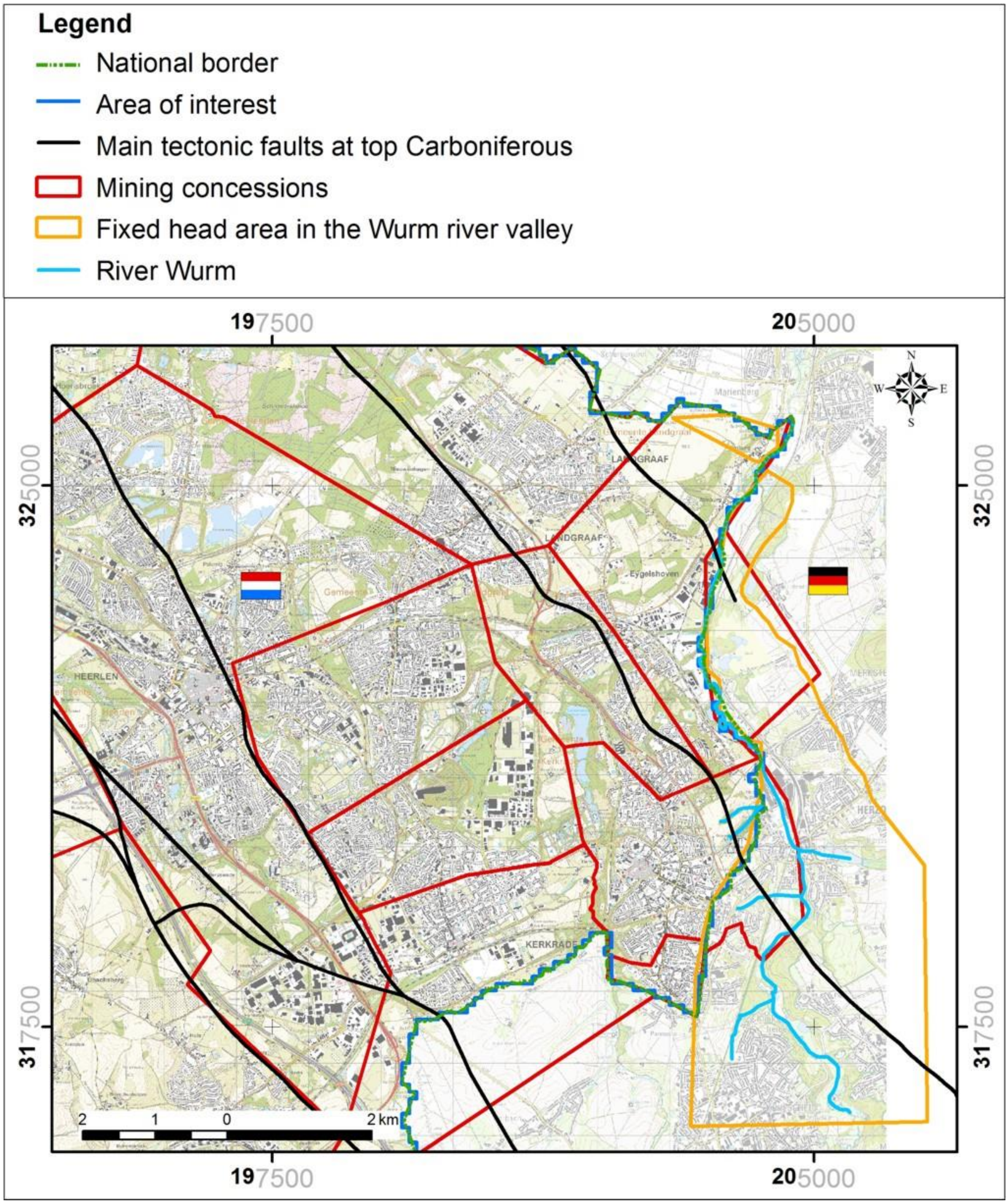


Fig. A3.1: The Wurm valley with the fixed head zone for the worst case secenario

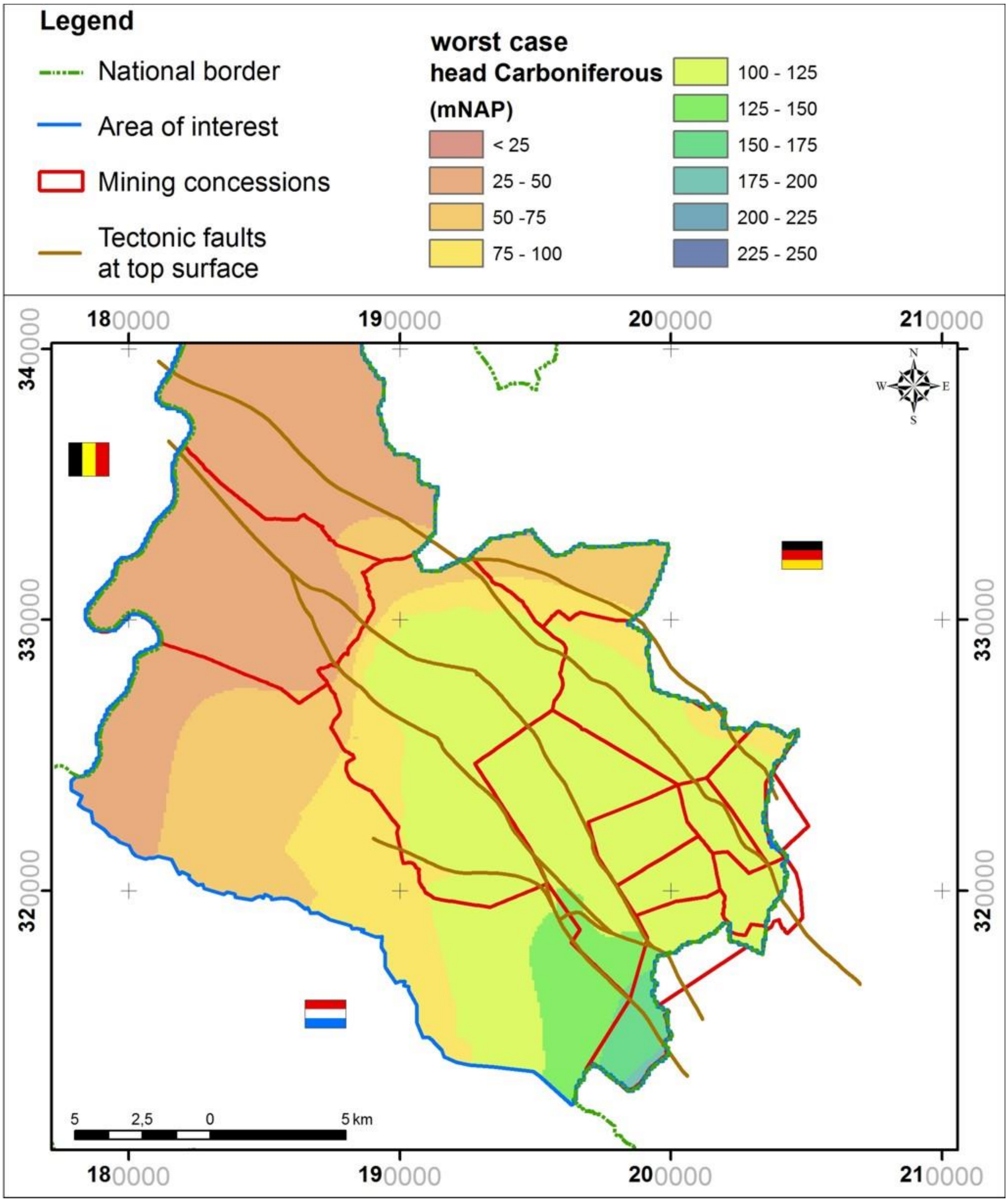


Fig. A3.2: Calculated groundwater head in the Carboniferous – worst case scenario

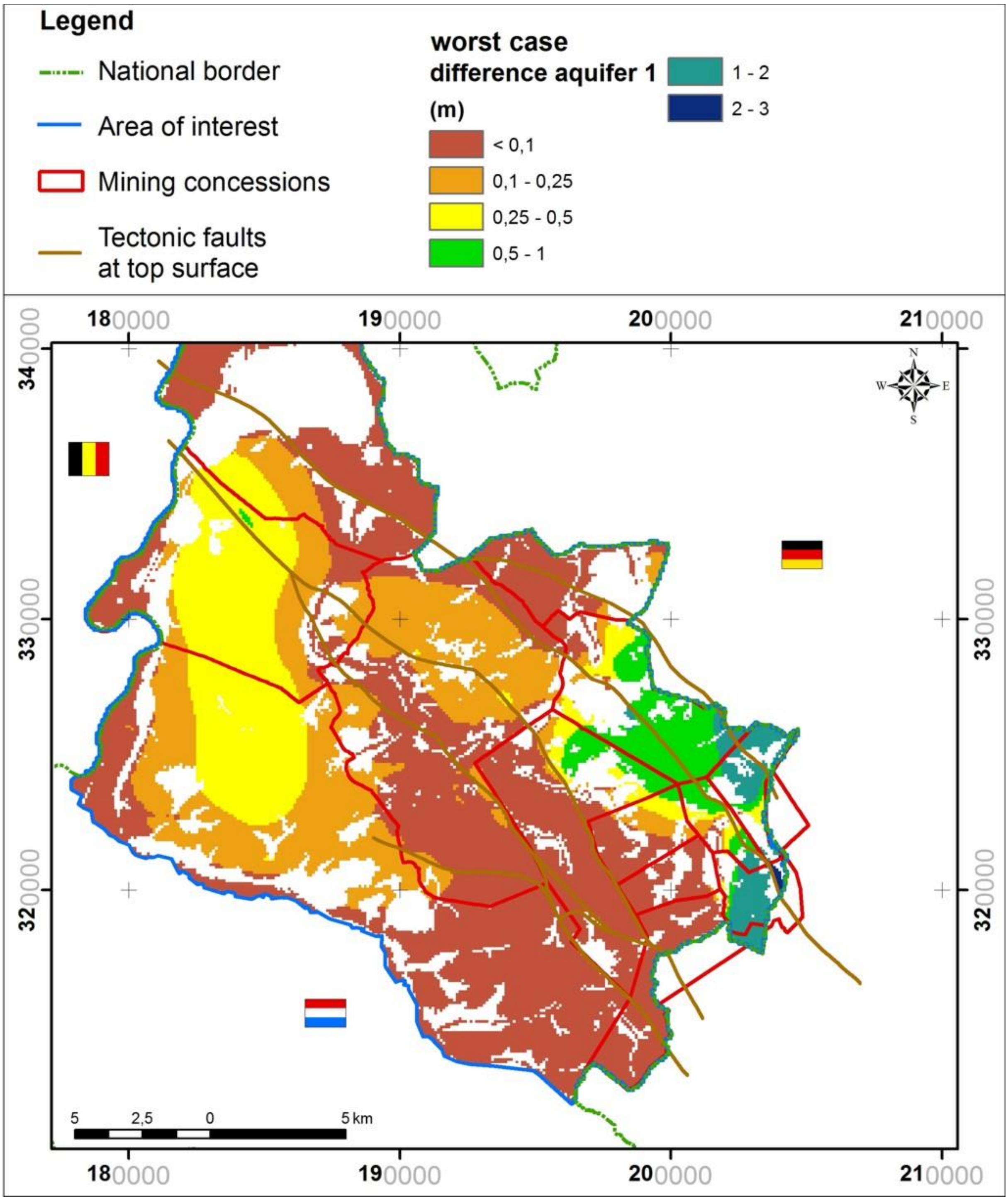


Fig. A3.3: Difference in phreatic groundwater head - worst case scenario

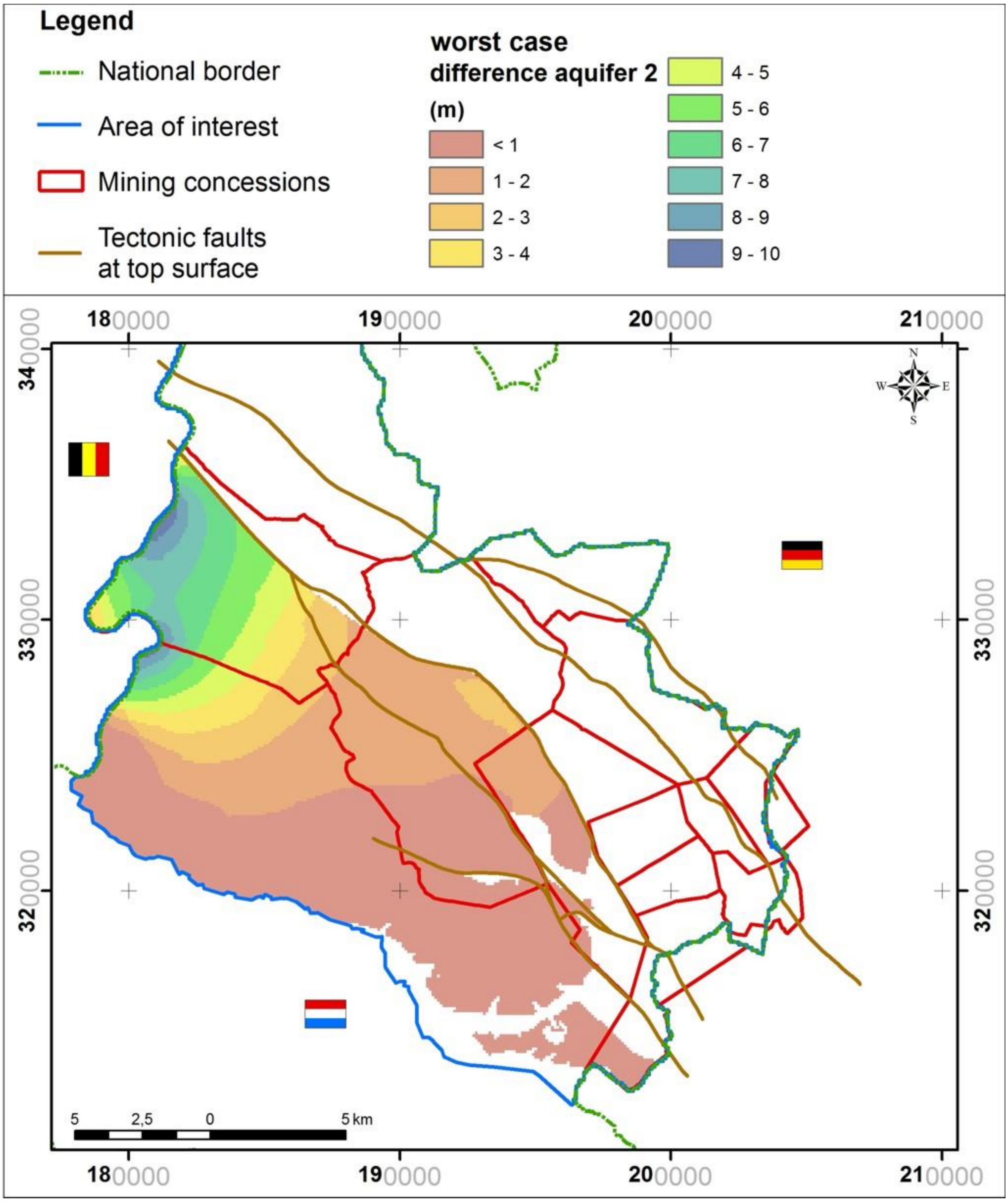


Fig. A3.4: Increase water pressure second aquifer - worst case scenario

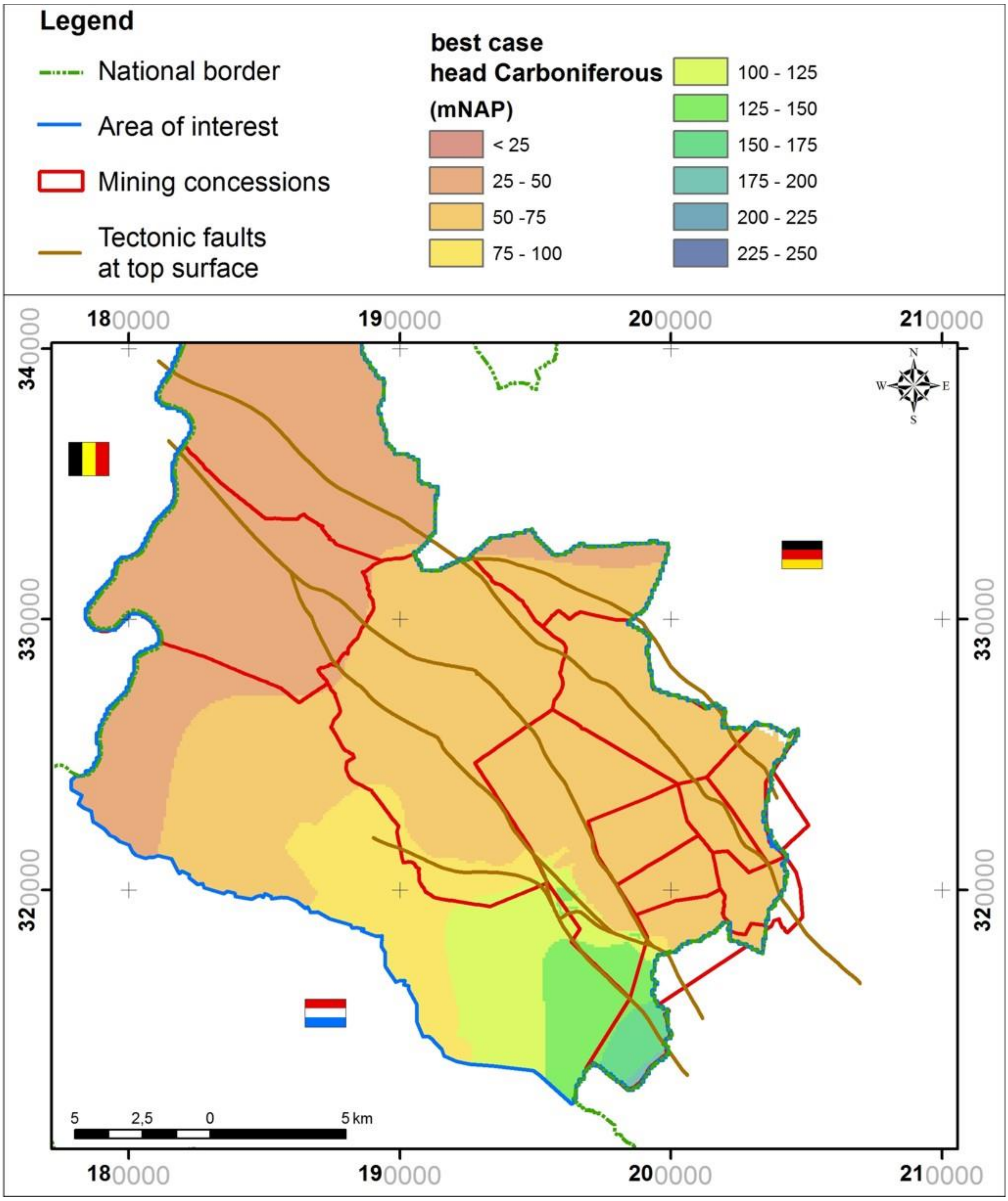


Fig. A3.5: Mine water pressure in the Carboniferous - best case scenario

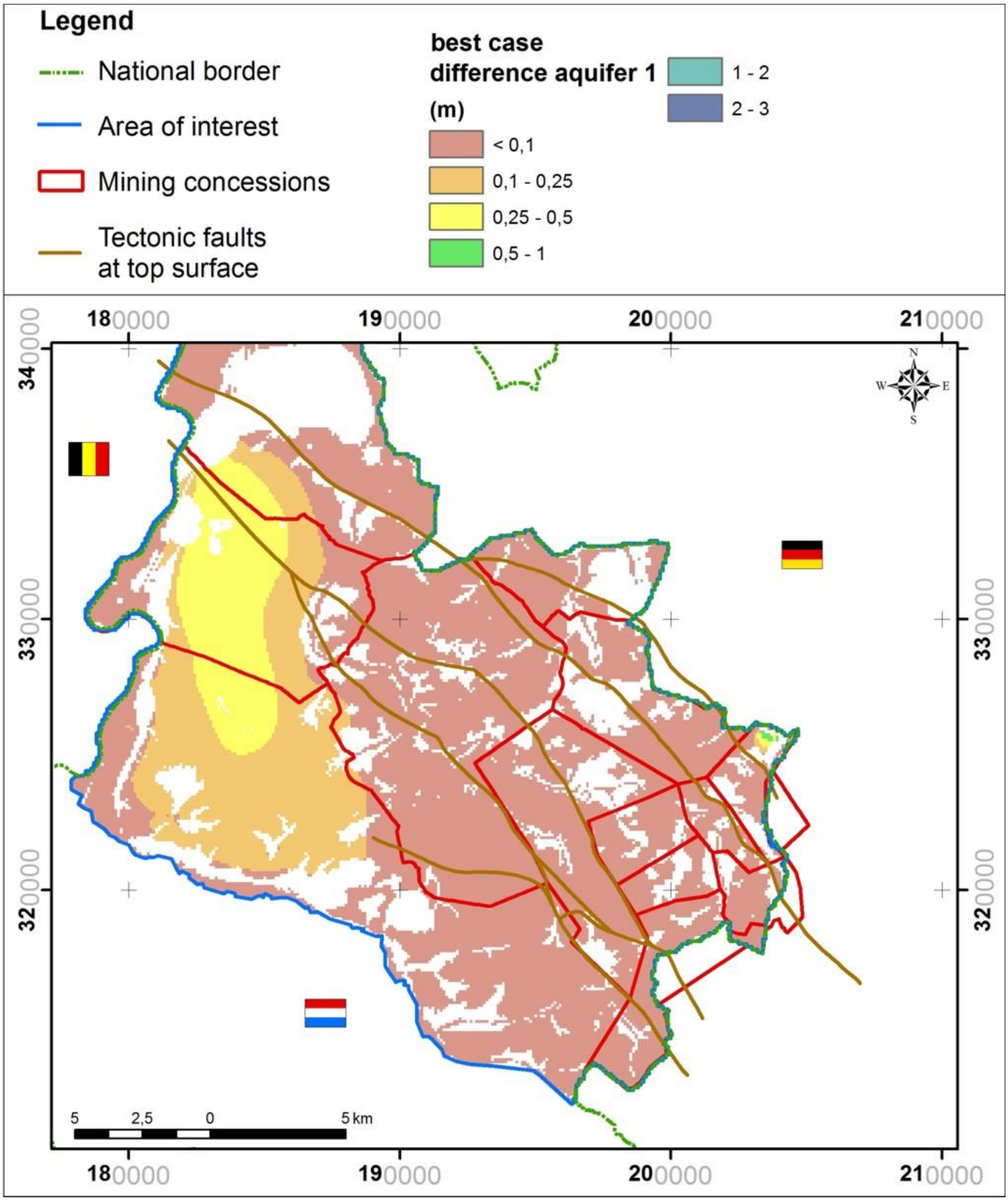


Fig. A3.6: Difference in phreatic groundwater table - best case scenario

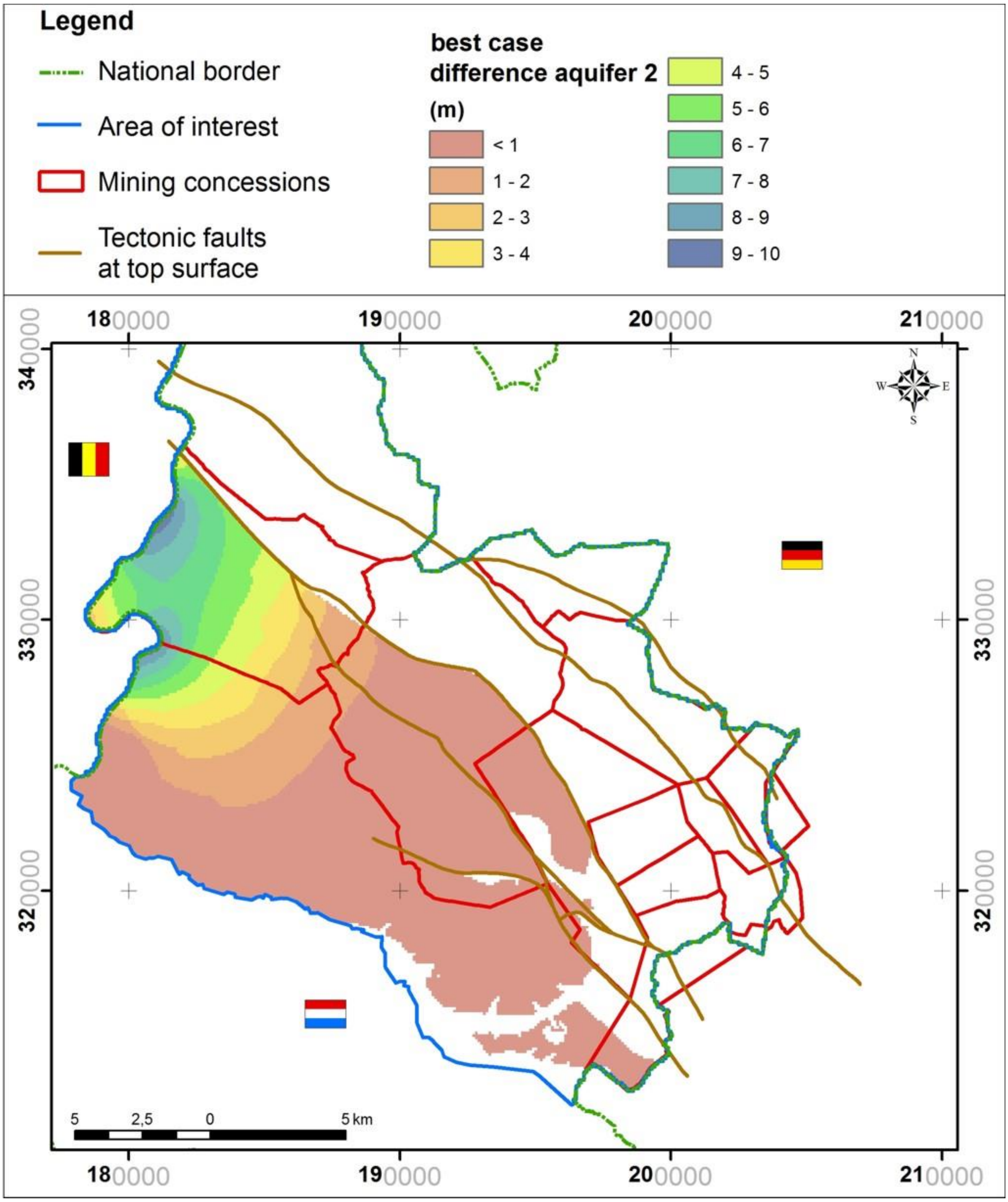


Fig. A3.7: Increase of groundwater head in the second aquifer - best case scenario

Appendix 4

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working groups
5.2.4 - groundwater quality
5.2.5 - groundwater quantity

Bow-Tie-diagram change groundwater quality

by

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"Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg"
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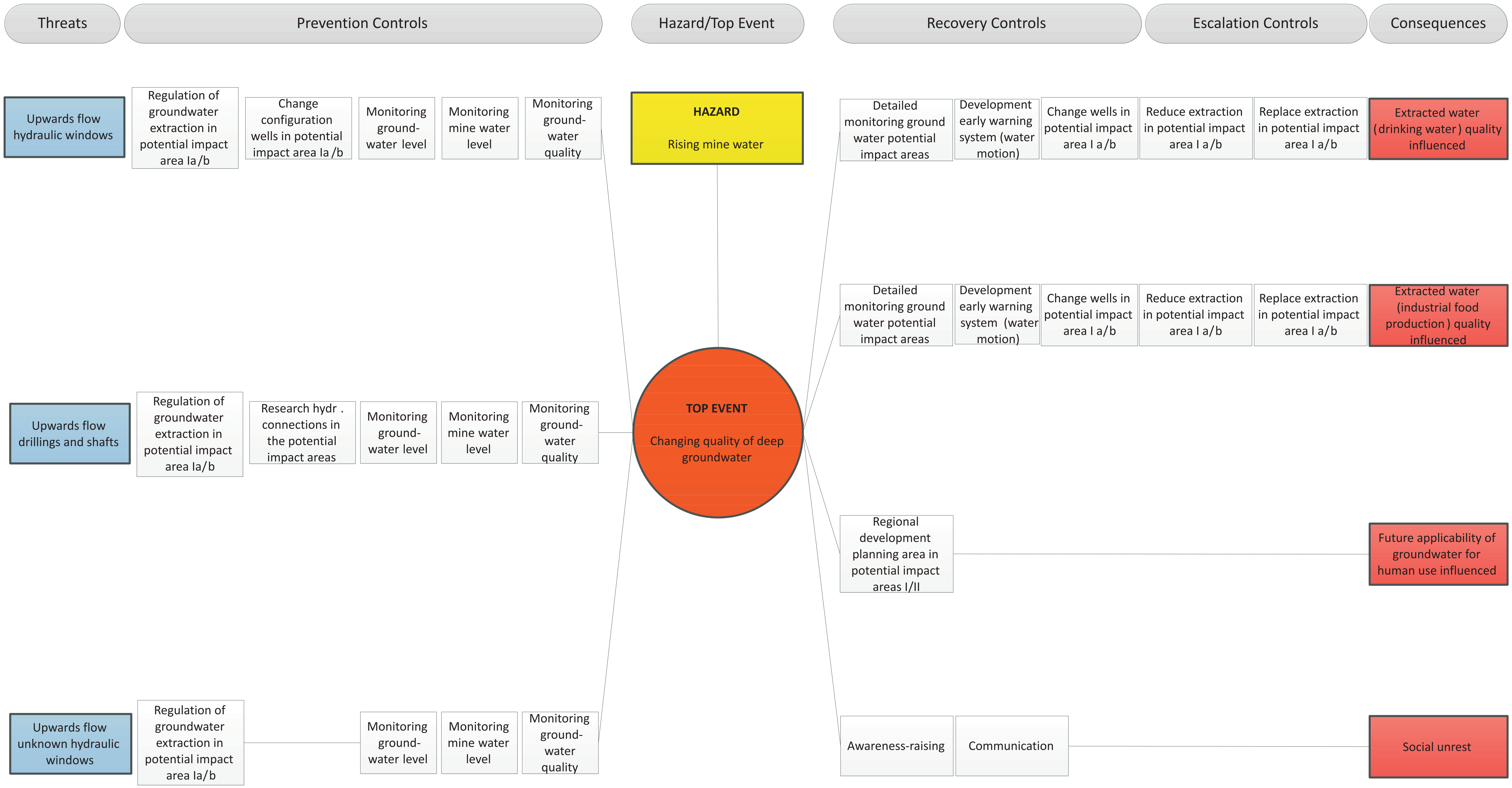
Aachen (D), Deventer (NL), 31. August 2016
(Rev. a: 02. December 2016)

5.2.4 Groundwater quality



Threats | Prevention Controls | Hazard/Top Event | Recovery Controls | Escalation Controls | Consequences

Upwards flow hydraulic windows | Regulation of groundwater extraction in potential impact area Ia/b | Change configuration wells in potential impact area Ia/b | Monitoring ground-water level | Monitoring mine water level | Monitoring ground-water quality

Upwards flow drillings and shafts | Regulation of groundwater extraction in potential impact area Ia/b | Research hydr. connections in the potential impact areas | Monitoring ground-water level | Monitoring mine water level | Monitoring ground-water quality

Upwards flow unknown hydraulic windows | Regulation of groundwater extraction in potential impact area Ia/b | Monitoring ground-water level | Monitoring mine water level | Monitoring ground-water quality

HAZARD

Rising mine water

TOP EVENT

Changing quality of deep groundwater

Detailed monitoring ground water potential impact areas | Development early warning system (water motion) | Change wells in potential impact area I a/b | Reduce extraction in potential impact area I a/b | Replace extraction in potential impact area I a/b | Extracted water (drinking water) quality influenced

Detailed monitoring ground water potential impact areas | Development early warning system (water motion) | Change wells in potential impact area I a/b | Reduce extraction in potential impact area I a/b | Replace extraction in potential impact area I a/b | Extracted water (industrial food production) quality influenced

Regional development planning area in potential impact areas I/II | Future applicability of groundwater for human use influenced

Awareness-raising | Communication | Social unrest

App. 4

Appendix 5

Na-ijlende gevolgen steenkolenwinning Zuid-Limburg

Final report
on the results of the working groups
5.2.4 - groundwater quality
5.2.5 - groundwater quantity

Bow-Tie-diagram wetting

by

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"Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg"
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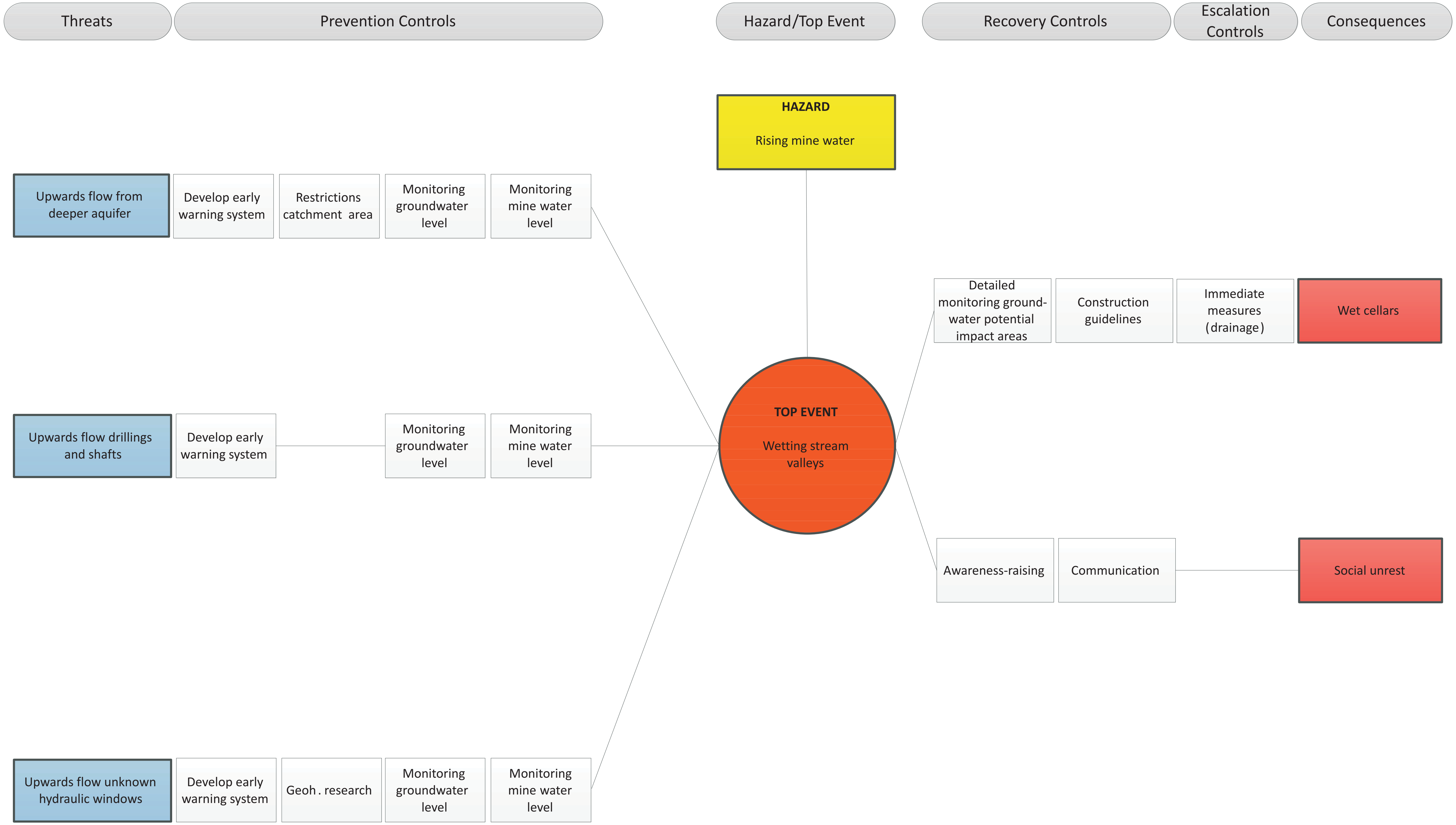
(Rev. a: 02. December 2016)

5.2.5 Groundwater quantity



Threats

Prevention Controls

Hazard/Top Event

Recovery Controls

Escalation Controls

Consequences

HAZARD

Rising mine water

Upwards flow from deeper aquifer

Develop early warning system

Restrictions catchment area

Monitoring groundwater level

Monitoring mine water level

Upwards flow drillings and shafts

Develop early warning system

Monitoring groundwater level

Monitoring mine water level

Upwards flow unknown hydraulic windows

Develop early warning system

Geoh. research

Monitoring groundwater level

Monitoring mine water level

TOP EVENT

Wetting stream valleys

Detailed monitoring groundwater potential impact areas

Construction guidelines

Immediate measures (drainage)

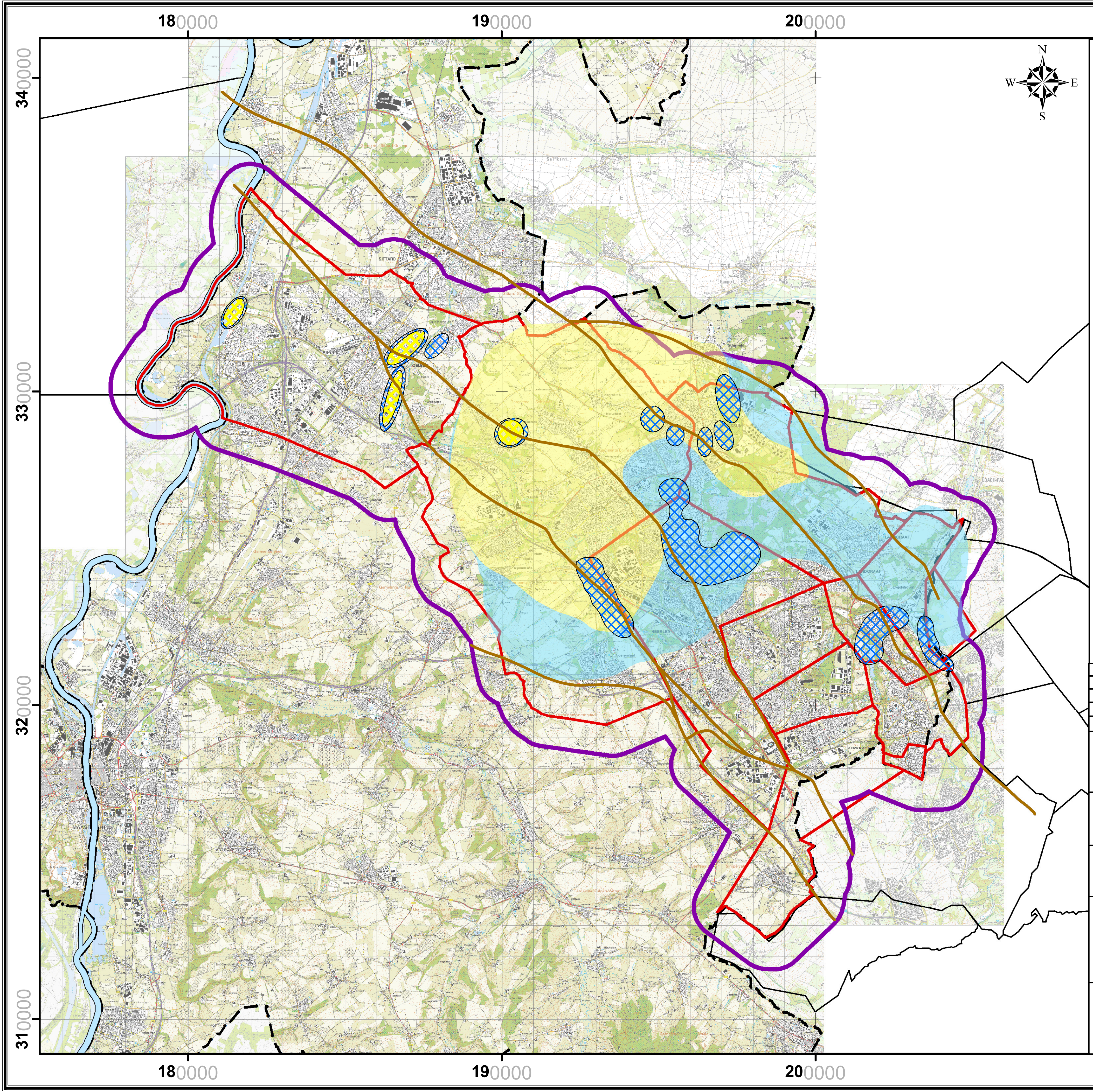
Wet cellars

Awareness-raising

Communication

Social unrest

App. 5



Legend

- ‐·‐·‐ National border
- ━ Project area
- ━ Mining concessions South Limburg
- ─ Mining concessions Belgium and Germany
- ━ Tectonic fault top surface

Potential impact areas

Changing quality of deep groundwater

- 🟨 average case scenario
- 🟦 worst case scenario

Wetting stream valleys

- ▨ average case scenario
- ▨ worst case scenario

base map: TOP25raster, sheets 68D Sittard, 68G Brunssum, 69B Maastricht, 69E Heerlen
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Rev.	Description	Date
b	legend	02.12.2016
a	mining concessions, tectonic faults	09.08.2016

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

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

Naming: Na-ijlende gevolgen steenkolenwinning Zuid-Limburg,
WG 5.2.4/5.2.5 - groundwater quality / quantity - final report

Potential impact areas, overview

Drawing No.: 107-17-001b

Edited:	Drawn:	Reviewed:	Scale
Name: P. Rosner Date: 31.08.2016	Name: M. Paffen Date: 31.08.2016	Name: M. Heitfeld Date: 31.08.2016	1:125.000 Plan 1

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