Development of a New Brine Cavern Field for Hengelo Salt Plant:

Phase III

Update of the Subsidence Prediction according to the Production Planning 2012

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Date:	11 September 2012

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1 Executive Summary

Surface subsidence will occur above the planned brine production cavern field near Haaksbergen as a consequence of salt creep. The creep response depends on different influencing parameters that are specific to the site. Subsidence depends on the general creep response and the process of cavern development.

The planning for the new brine field near Haaksbergen started with a preliminary design phase, where first project relevant parameters were determined on the basis of best knowledge and experience. In the meantime site specific data were collected during phase II of the planning process improving the knowledge base particularly in terms of geological and geomechanical characterization of the Haaksbergen salt deposit.

The subsidence predictions presented in this report are based on the information collected during phase II (exploration) of this project. The production planning of DEEP. 2012, which is based on the same information, describes the location of the caverns in the field and their development over time. The production planning provides input data for the subsidence predictions. While the brine production planning of DEEP. 2012 describes the development of an entire field of 36 caverns (in three phases of 12 caverns), AkzoNobel will apply for a solution mining permit for 12 brine production caverns only. To provide an overview of subsidence development, the predictions are presented for both: phase 1 alone and phases 1 to 3 combined. The next step comprises the adjustment of the basic rock-mechanical cavern model for the calculation of representative convergence rates. This means that in particular the results from lab tests on core material of the exploration well ISH-01 and the cavern size and depth location according to the updated production planning were taken into account.

Predictions of the expected surface subsidence over time are given for two different scenarios. The Worst Case Scenario represents conservative assumptions in terms of expected convergence rates during production and after abandonment. The Base Case Scenario takes a more realistic value of the convergence rate after abandonment and the average depth location of all caverns with regard to the current production planning into account.

For the calculation of the surface subsidence the widely accepted code of SaltSubsid, which is distributed by SMRI, was used.

Surface subsidence in terms of vertical displacements as well as subsidence rates are presented in maps superimposed to the topographical map of the project area near

Haaksbergen. Two timeframes (20 and 50 years after start of the mining operation) were selected in order to demonstrate the development of the subsidence bowl over time.

The subsidence bowl principally follows the progress of the production process. As brine production starts in the eastern part of the cavern field, surface subsidence starts here and progresses into a western direction. The maximum value of subsidence remains in the eastern part of the field. As surface subsidence directly depends on cavern convergence as well as on the existing or created cavern volume, the rate of subsidence slows down towards the end of the production phase, because additional cavern volume is not created at the same rate as before while at the same time the number of abandoned caverns increases. The abandonment period in the prediction model is considered by assuming a smaller convergence rate. Thus, the global rate of volume convergence is reduced and the long-term rate of subsidence is predicted to be about 5 mm/year for the Worst Case Scenario and 3 mm/year for the Basic Scenario considering caverns of production phase 1 only.

Predicted values for the maximum subsidence in the centre of the subsidence bowl after 20 and 50 years for all scenarios are summarized in Table 1. Maximum values after 50 years with reference to predictions for Haaksbergen vary between 25 and 43 cm. If the creep ability of Heiligerlee rock salt is considered, a maximum subsidence of 21 cm is predicted as a result of leaching 36 caverns.

At first glance it seems remarkable that maximum subsidence values predicted for 70 caverns of planning phase I lead to almost the same maximum subsidence as for 12 caverns considered in phase III of the planning process. However, the following matter must be taken into account:

- the volumes of phase III caverns are slightly increased due to the greater thickness of the salt based on the results from phase II investigations in comparison with the phase I assumption for salt thickness;
- the expected convergence rates of the caverns are higher because the lab tests of site specific cores from the exploration well ISH-01 revealed a higher creep ability of the Haaksbergen salt than the adopted creep used in planning phase I; and
- the representative creep rate of the caverns is higher because of a deeper average depth location of the caverns, which results from the detailed geological site characterization during phase II investigations.

In general one has to consider that the assumed constant convergence rates after cavern abandonment even in the Base Case Scenario still represent conservative assumptions for the long term. After cavern abandonment the creep rate of the plugged caverns decays relatively fast to very small values. More definite values can only be calculated on the basis of a detailed cavern abandonment study that will be carried out during a later stage of the project. Furthermore, creep parameters of the Haaksbergen salt may vary across the salt structure. With a growing number of wells and therefore an increasing number of test results of cores from different wells, the average creep ability of the Haaksbergen salt could possibly turn out to be lower than the values currently used in the subsidence prognosis.

Table 1: Predicted maximum subsidence according to the studied scenarios

Point in Time after Start of Mining Operation [years]	Preliminary Scenario of Planning Phase I Scenario 1a 70 caverns [m]	Preliminary Scenario of Planning Phase I Scenario 1b 36 caverns [m]	Worst Case Scenario Scenario 2 12 caverns [m]	Basic Scenario Scenario 3 12 caverns [m]	Worst Case Scenario Scenario 2 36 caverns [m]	Basic Scenario Scenario 3 36 caverns [m]	Reference Scenario Heiligerlee Scenario 4 36 caverns) [m]
20	0.19	0.16	0.17	0.15	0.19	0.16	0.11
50	0.44	0.32	0.34	0.25	0.43	0.33	0.21

2 Introduction

AkzoNobel intends to create a new brine production cavern field near Haaksbergen, which is close to the Hengelo Salt Plant, in order to ensure the supply of brine for future salt production. The planning process for the new cavern field is organized in three successive phases:

- Phase I contained the basic planning of the rock-mechanical layout and leaching concept as well as the geological and technical planning for the exploration well ISH-01.
- Phase II comprised the drilling and evaluation of exploration well ISH-01 at Isidorushoeve, The Netherlands.
- In Phase III the basic documents are drafted for the permit application procedure.

DEEP. Underground Engineering GmbH (DEEP.) was appointed by AkzoNobel for general support in the planning process with regard to site characterization and exploration as well as brine production planning. KBB Underground Technologies GmbH (KBB UT) takes part in this planning process as a subcontractor for rock-mechanical and subsidence issues in cooperation with the Institut für Gebirgsmechanik, Leipzig (IfG).

The present study was performed within the scope of Phase III in order to provide a basic prediction on surface subsidence due to the planned brine production near Haaksbergen as proposed by DEEP. in 2012 [1]. Based on this production plan surface subsidence can be predicted by taking into account the development of the cavern field, e.g. in terms of number of caverns as well as their individual volume increase over time, and the resulting convergence of these caverns.

In this report a general overview of subsidence modelling is given in Chapter 3. The basic assumptions for the set-up of the subsidence model as well as the applied step by step concept for subsidence prediction near Haaksbergen are described in Chapter 4. This Chapter also describes the different phases of the cavern field development and manner in which they relate to the subsidence prediction. The results of the calculations are discussed in Chapter 5 and shown using contour maps related to the topography near Haaksbergen. The contour maps show vertical displacements (maps of isocatabases) as well as displacement rates for selected points in time.

3 General Aspects of Surface Subsidence Modelling

The basic understanding of mining induced surface subsidence is that it is caused by volume losses in the subsurface. These volume losses can be a consequence of convergence of mined cavities or they can result from pressure release in fluid filled pores of a reservoir. Surface subsidence modelling refers to the practice of predicting the subsidence on the basis of the planned mining activities using numerical models that describe the correlation between subsidence and mining activity.

In surface subsidence prediction an assumption has to be made on the mechanism which describes how volume losses in the subsurface are transferred to the surface. This means the shape of the subsidence bowl, which will develop at the surface, has to be generally characterized. Apart from the shape of the bowl also the lateral extent and the relationship between bowl development and volume loss in the subsurface need to be established.

With respect to salt caverns, the development of subsidence over time is a direct consequence of the creep behaviour of salt.

A generally accepted model for subsidence induced by salt creep caused by the development of caverns in rock salt was developed by SROKA and SCHOBER (1982) [2] and generalized by EICKEMEIER (2005) [3]. This subsidence model is implemented in the SaltSubsid software that is used for predictions within the scope of this study. The SaltSubsid software is distributed by the Solution Mining Research Institute (SMRI), USA and represents well-accepted standard software for the calculation of surface subsidence above mines and caverns located in salt structures. More detailed information about the theoretical background of implemented models and their input parameters is given in the SaltSubsid user’s manual [4]. However, the general outline of the applied model and the input parameters required are briefly presented below while the governing formulae describing the SROKA/SCHOBER model are given in Appendix A.

The concept of the SROKA/SCHOBER subsidence model can be summarized in principle as follows:

- A normalized Gaussian type is used as shape function of the subsidence bowl (or trough), which is influenced by a set of parameters. Of these parameters the angle of draw β, the bulking factor *a* of the overlying rocks during subsidence movements and the cavern convergence rate $V_C(t)/dt$ are of major importance.
- The angel of draw β determines the surface area that is influenced by the volume losses $V_C(t)$ in the subsurface. It is measured against the horizontal and related to a representative cavern depth.
- The bulking factor *a* describes the ratio of convergence volume produced in the subsurface compared to the subsidence volume appearing at surface.
- The convergence rate $V_C(t)/dt$ describes the loss of cavity volume over time.

4 Concept of Haaksbergen Subsidence Modelling

4.1 Leaching Concept and Production Planning

The applied subsidence prediction model is based on the leaching concept for the new cavern field near Haaksbergen, which was presented by DEEP. in 2012 [1].

According to this concept 36 caverns will be developed by solution mining. A rock-mechanical study was performed by IfG in order to demonstrate that a stable rock-mechanical envelope can be achieved. For this general proof of stability a cavern with a maximum diameter of 135 m was assumed. However, in order to reduce the potential for subsidence the maximum diameter of the caverns for production planning purposes was restricted to 125 m. Furthermore, as irregularities in the leaching process of a cavern must always be considered, a utilization factor of 80 % (leached volume vs. rock-mechanical volume) is taken into account. This means that a cavern with an average diameter of 112 m within a rock-mechanical envelope of 125 m can be developed in a safe and stable manner.

Four cavern types were differentiated by height (ranging between 137.5 and 287.5 m) according to the assumed local thickness of the salt layer. The cavern types and the distribution of caverns throughout the cavern field are shown in Enclosure 1.

The development of the cavern field over time is taken into account as described in the DEEP. production planning and leaching concept [1]. The whole production phase is subdivided in three phases. In each phase 12 caverns are planned to be developed. The solution mining operations are assumed to start with phase 1 at the beginning of 2015 and the last cavern of phase 1 will be finalized in 2039. The last cavern of the project phase 3 will be finalized in 2059. The cavern field will be developed from east to west. The growth of the cavern volume over time is given individually with regard to the different cavern types in the leaching concept and is taken into account in the subsidence model.

4.2 Cavern Convergence

4.2.1 Introduction

With respect to the brine production caverns, the ability of the surrounding rock salt mass to creep continuously leads to volume losses of the caverns (convergence) and therefore subsidence at the surface. The driving force of the creep process is the difference between the pressure in the brine filled cavern and the stress in the surrounding rock. As the creep process proceeds, subsidence increases over time. However, the rate of volume convergence can be limited to small values, when the pressure in the caverns is maintained at relatively high levels. This is especially relevant in the post leaching phase after brine production. Finally, when the caverns have been sealed, the convergence rate will continuously decrease to very small values during the abandonment phase, because the driving force for creep diminishes due to an increasing internal cavern pressure. In the applied SaltSubsid model the different convergence rates are considered according to the different phases in the lifetime of a cavern. Individual creep rates with respect to the different operation modes (brine production/post production/abandonment) are assumed.

4.2.2 Initial values for convergence

First estimates of the cavern convergence were made on the basis of the preliminary design model of IfG that has been developed within phase I of the project. A model with a maximum radius of 135 m located at a depth range between 715 and 915 m was applied. Due to the lack of site specific data at that stage of the planning process, the creep ability of the salt was assumed by IfG based on experience. Results of this rock-mechanical study formed the basis of the preliminary subsidence prediction (Scenario 1). Convergence rates of 0.2 %/year during brine production and of 0.04 %/year at a wellhead pressure of 50 bars were calculated. The rate calculated for 50 bars wellhead pressure thereby was assumed to represent the convergence rate after cavern abandonment.

4.2.3 Updated values for convergence

Conservative estimates on volume convergence of the planned caverns, which consider specific conditions near Haaksbergen, were provided by the rock-mechanical study of IfG carried out in 2012 [11]. The convergence rates of an updated generic type of a brine production cavern near Haaksbergen were calculated which is referred to as the basic cavern model in the following. The basic cavern model represents a maximum cavern diameter of 125 m in a hexagonal field layout with a cavern spacing of 300 m. These boundary conditions are matching the leaching concept of DEEP. 2012. Material characteristics of the rock salt are derived from the results of laboratory tests performed by IfG using core material from the exploration well ISH-01 [6].

The basic cavern model represents one of the deepest and tallest caverns of the DEEP. 2012 production planning [1], i.e. the calculated convergence rates can be regarded as conservative, if applied to all caverns of the field. The limiting parameters of the rock-mechanical shape are represented in Enclosure 2.

With reference to the alignment of caverns within the cavern field, the selected basic cavern model represents a cavern that is situated in the centre of an endless hexagonal cavern field, i.e. a cavern with six neighbouring caverns to all sides in a hexagonal grid. Calculated steady-state values for a cavern convergence rate are given by IfG at 0.553 %/year during cavern operation considering atmospheric wellhead pressure, and 0.117 %/year at wellhead pressure of 50 bars. In the subsidence model the first value is applied for the leaching and subsequent post leaching phase and a time span of one year after finalization of brine production. The second value is used for the period after cavern abandonment. The time span needed for preparing the caverns for sealing may be longer for the first caverns because of a principle testing phase. However, an interval of one year seems to be a reasonable average value when taking into account a total of 36 caverns. Compared with the preliminary convergence rates of the design phase the values calculated for the basic simulation model are higher because of two reasons: (1) The applied creep characteristics of the tested ISH-01 cores revealed a faster creep response than estimated for the preliminary design scenario and (2) the location of the applied basic cavern model is deeper.

4.2.4 Influence of field layout and cavern depth on convergence values

The field development according to the production planning of DEEP. 2012 shows that the caverns have on average four neighbouring caverns instead of six. This leads to a reduction of the expected convergence rate, because on average the remaining salt pillar that is utilized for the load bearing is larger than that of a typical field cavern with six neighbouring caverns in an endless field layout pattern. Therefore, IfG additionally calculated the convergence rates for a cavern with four neighbouring caverns resulting in values of 0.252 %/year during cavern operation and 0.0483 %/year at a wellhead pressure of 50 bars. In order to consider the individual ratio of average pillar to cavern diameter for every cavern in the field an empirical relationship was developed that is represented in Enclosure 3. This empirical formula is based on the calculated results of IfG and the findings of GAULKE ET AL. (2007) [8] and ZANDER-SCHIEBENHÖFER (2007) [9]. On average a cavern in the planned brinefield has four neighbours. Therefore, the convergence rate of this typical cavern is also stated in Table 3, which summarizes principal characteristics of the different scenarios that have been studied.

The above mentioned values for cavern convergence rates and field layout considerations were used in the conservative scenario for subsidence prediction, which is referred to as the Worst Case Scenario (or Scenario 2).

In order to present more realistic subsidence predictions, an additional scenario was studied, which takes into account the depth location of the prospected caverns and the abandonment phase in greater detail. This scenario is considered as the Base Case Scenario (or Scenario 3) for the subsidence prediction of Haaksbergen.

According to the production planning of DEEP. 2012, the selected basic cavern model represents one of the deepest caverns in the entire field. Due to this, it can be assumed that the convergence rates calculated by IfG are conservative. Consequently a further reduction of the convergence rates by 10 % is assumed. This can be justified by comparing the individual creep response of the rock salt mass at depths of 880 m and 910 m as shown in Enclosure 4. The analytical creep formula, which is applied in order to calculate the presented values, was published by V. SAMBEEK (1993) [7]. It takes into account the steady-state creep response of a cylindrical cavern in a rock salt formation and describes it by a power law. The above mentioned depth of 910 m represents the reference depth of the basic cavern model as used by IfG in 2012; the reference depth of 880 m is deducted from the average depth location of all caverns according to the production planning concept of DEEP. 2012 and therefore represents the most realistic value. Thus, the convergence rate during the production phase is reduced to 0.5 %/year.

After cavern abandonment the internal cavern pressure can be expected to rise faster than it is represented on average by a constant wellhead pressure of 50 bars; assumed by IfG as a representative value for the first years after plugging. According to the results of a scoping calculation for the internal cavern pressure increase of a cavern at a depth of 880 m (see Enclosure 5), the convergence rate drops relatively fast with an increasing internal cavern pressure. After 20 years the average convergence rate is reduced to about 10 % of the initial value. Therefore, a 33 % reduction of the convergence rate after abandonment is considered in prediction Scenario 3, resulting in a convergence rate of 0.07 %/year. With regard to the average cavern of the planned field having four neighbours, the assumed convergence rate for this scenario is 2.27%/year during operation and 0.32%/year respectively after cavern abandonment (see Table 3).

Nevertheless, even the assumed convergence rates for the Base Case Scenario (Scenario 3) can be considered as slightly conservative. In reality, the pressure built-up in a cavern after plugging will lead to very low convergence rates within the first decades after abandonment. However, this development of convergence rate after abandonment can only realistically be considered if the abandonment process is simulated in a numerical study, which is planned to be performed by IfG later in the field development process.

4.3 Bulking Factor and Angle of Draw

While the cavern convergence was calculated based on the selected cavern design and location as well as site specific material behaviour, parameters like the bulking factor a and the angel of draw β are estimated based on experience. Within the scope of this study the bulking factor a is assumed to be 1. This means that the convergence volume and consequently the surface subsidence volume are of the same value and as such can be considered as a conservative assumption.

The angle of draw differs from location to location and can change over time of operation due to the long-term creep of the salt. However, in the applied SaltSubsid code only fixed values for the angle of draw can be entered as input parameter. With regard to long-term subsidence observations above salt caverns, this value can be assumed to range between 35° and 45°. Over long periods it is likely that the angle of draw will become smaller due to the overall creep behaviour of the salt deposit (see [8] and [9]). Therefore, within the scope of the present study, an angle of draw of 40° was selected which can be considered as a reliable value with regard to subsidence predictions above the planned caverns near Haaksbergen. In principle an assumed lower value of the angle of draw leads to the prediction of smaller subsidence values while the surface area of the subsidence bowl will be larger.

It can be assumed that the applied value of 40° for the angle of draw, which is used in all studied scenarios, represents a slightly conservative assumption with regard to subsidence in the long-term as well as slightly progressive in terms of the lateral extension of the subsidence bowl.

4.4 Field Development

The overall planning of AkzoNobel for the brine production near Haaksbergen comprises three phases. Within each phase 12 caverns are intended to be developed. Once the designated volume in compliance with the rock-mechanical recommendations has been reached, the caverns will be plugged and abandoned. The duration of the phases are prospected as compiled in Table 2.

AkzoNobel will apply for permission for phase 1 only at this time. Therefore, the presented subsidence predictions are focused on phase 1 in which 12 caverns will be developed.

Table 2: Planned phases of brine production near Haaksbergen

	Start of Production	End of Production	No. of Caverns acc. to Phase	No. Caverns in total
Phase 1	2015	2039	12	12
Phase 2	2025	2052	12	24
Phase 3	2039	2058	12	36

4.5 Overview of Studied Scenarios

The development scenarios for which the expected subsidence is studied are closely linked to the planning process for the Haaksbergen site. Initially two preliminary scenarios (Scenario 1a and 1b) were examined in order to get a general impression on the capabilities and consequences (in terms of subsidence) of cavern development by taking into account 70 (Scenario 1a) as well as 36 caverns (Scenario 1b). While Scenario 1a represents a kind of maximum design with 70 caverns, the effect of reducing the number of caverns and the individual cavern size is analysed in Scenario 1b. In the subsequent two scenarios the updated knowledge base was considered, i.e. the collected data from planning phase II investigations was taken into account. The knowledge increased particularly in terms of geological characterization of the salt structure and site specific mechanical behaviour of the salt. Furthermore, AkzoNobel’s actual brine production demand was incorporated in the updated production plan of DEEP. 2012, which is based on the latest information from geological interpretation. By comparing Scenario 2 and Scenario 3 with the initial Scenario 1b, the influence of the change in the production planning and the improved knowledge base on the subsidence can be demonstrated. Scenario 4 was calculated in order to provide a reference with a well-known rock salt characteristic. The creep behaviour of the Heiligerlee rock salt is assumed in this scenario by reducing of the creep ability by 65% compared to the Haaksbergen (ISH-01) rock salt.

Although AkzoNobel is currently applying for the solution mining permit for 12 caverns only, Scenario 2 and Scenario 3 were also evaluated for 36 caverns in order to give an idea of the subsidence development, if the entire cavern field is created (production phase 1 to phase 3).

An overview of the basic assumptions for the studied scenarios for the surface subsidence prediction near Haaksbergen is given in Table 3**.**

Table 3: Overview of subsidence prediction scenarios

Scenario	Description	Production Model	Generic Rock Mechanical Model	Material Parameters for Creep	Angel of Draw [°]	Calculated Convergence Rate during Operation (Field Cavern) [‰/year]	Calculated Convergence Rate after Abandonment (Field Cavern) [‰/year]
1a	**Preliminary design scenario – maximizing production**	DEEP. 2011 70 caverns	Diameter 135 m Depth range 750 to 915 m	Assumed by IFG's experience with testing of Z1 material	40	**2**	**0.4**
1b	**Preliminary design scenario – reducing subsidence**	DEEP. 2011 36 caverns	Diameter 125 m Depth range 750 to 915 m	Assumed by IFG's experience with testing of Z1 material	40	**2**	**0.4**

Table 3 (continued): Overview of subsidence prediction scenarios

Scenario	Description	Production Model	Generic Rock Mechanical Model	Material Parameters for Creep	Angel of Draw [°]	Calculated Convergence Rate during Operation (Field Cavern) [‰/year]	Calculated Convergence Rate after Abandonment (Field Cavern) [‰/year]
2	**Worst Case scenario**	DEEP. 2012 12 and 36 caverns	Diameter 125 m Depth range 715 to 1,007 m	Determined from lab test results of ISH-01 core material	40	**5.53** **including the consideration of** • the individual pillar situation **cavern with 4 neighbours 2.52**	**1.17** **including the consideration of** • the individual pillar situation **cavern with 4 neighbours 0.53**

Table 3 (continued): Overview of subsidence prediction scenarios

Scenario	Description	Production Model	Generic Rock Mechanical Model	Material Parameters for Creep	Angel of Draw [°]	Calculated Convergence Rate during Operation (Field Cavern) [‰/year]	Calculated Convergence Rate after Abandonment (Field Cavern) [‰/year]
3	**Base Case scenario**	DEEP. 2012 12 and 36 caverns	Diameter 125 m Depth range 715 to 1,007 m	Determined from lab test results of ISH-01 core material	40	**4.98** **including the consideration of** • the individual pillar situation • a 10 % reduction convergence rate due to a shallower average cavern depth **cavern with 4 neighbours 2.27**	**0.7** **including the consideration of** • the individual pillar situation • a 10 % reduction convergence rate due to a shallower average cavern depth a 33 % reduction of the convergence rate within a period of 50 years after abandonment **cavern with 4 neighbours 0.32**

Table 3 (continued): Overview of subsidence prediction scenarios

Scenario	Description	Production Model	Generic Rock Mechanical Model	Material Parameters for Creep	Angel of Draw [°]	Calculated Convergence Rate during Operation (Field Cavern) [‰/year]	Calculated Convergence Rate after Abandonment (Field Cavern) [‰/year]
4	**Reference Scenario Heiligerlee**	DEEP. 2012 36 caverns	Diameter 125 m Depth range 715 to 1,007 m	Determined from comparing lab test results of ISH-01 core material with known creep test results on Heiligerlee material	40	**3.24** **including the consideration of** • the individual pillar situation • a 10 % reduction convergence rate due to a shallower average cavern depth **cavern with 4 neighbours 1.47**	**0.46** **including the consideration of** • the individual pillar situation • a 10 % reduction convergence rate due to a shallower average cavern depth • a 33 % reduction of the convergence rate within a period of 50 years after abandonment **cavern with 4 neighbours 0.21**

5 Results of the Surface Subsidence Modelling

The results of the subsidence predictions are only presented by maps (see Enclosures 7 to 22) for Scenario 2 and Scenario 3, because they are representing the currently assumed boundary conditions of the production planning and the up–to-date knowledge on the salt deposit near Haaksbergen. With reference to Scenario 1a, 1b and 4 only the maximum values of subsidence after 20 and 50 years from start of production are given in the concluding chapter in order to compare it with the equivalent values of the other scenarios. By this, the effect of the adaptations, which were made during the planning process in order to meet AkzoNobel's needs and the intention to reduce the subsidence, can be demonstrated.

Results of the subsidence predictions are presented in terms of vertical displacement and vertical displacement rate, which are referenced to a topographic map of the project area near Haaksbergen. The selected timeframes are 20 and 50 years after the start of development of the first cavern in order to show how the subsidence bowl develops over time. The results of the studied Scenario 2 and Scenario 3 are separately described in the following; the different results considering 12 or 36 caverns are also discussed. In Table 4 scenarios and corresponding Enclosures, which show the calculated results, are listed.

Table 4: Studied scenarios and their related enclosures

Scenario	Considered No. of Caverns	Description	Enclosures
2	12	Worst Case scenario	7 to 10
2	36	Worst Case scenario representing phase 1 to 3 field development	11 to 14
3	12	Basic scenario	15 to 18
3	36	Basic scenario representing phase 1 to 3 field development	19 to 22

5.1 Results of the Worst Case Scenario

Due to the fact that the proposed brine field development sequence starts in the eastern part of the cavern field, the subsidence bowl develops from east to west (see Enclosures 7 and 8). Consequently the predicted maximum value of surface subsidence appears in the eastern part of the cavern field and stays there during the entire evaluation period. Relative maximum values of subsidence can be identified along a virtual centre line through the surface projection of the developed cavern field for each time interval.

The increase of subsidence for this scenario over time is shown in Table 5, where the predicted maximum values are compiled for selected timeframes. In Enclosures 7 and 8 a graphical presentation of the subsidence shows that the area affected by the subsidence trough extends over time while the maximum subsidence values increase.

Table 5: **Scenario 2** – Increase of subsidence with time in the centre of the subsidence bowl

Time after Start of Production [years]	**Maximum Subsidence in the Centre of the Bowl (12 Caverns) [m]**	**Maximum Subsidence in the Centre of the Bowl (36 Caverns) [m]**
20	0.17	0.19
50	0.34	0.43

The maximum subsidence rate (vertical displacement rate) increases during the first 20 years of production up to about 13 mm/year (see Enclosure 9) and slows down to values of about 5 mm/year after the end of cavern development (see Enclosure 10) while the area affected by this displacement rate stays more or less the same.

If all three development phases (i.e. 36 caverns) are considered, a secondary subsidence bowl will develop in the western part 50 years after start of the development of the first cavern (see Enclosure 12). Due to this higher number of caverns, the lateral extent of the subsidence bowl is larger and the maximum subsidence will increase (compare Enclosures 8 and 12). Between 20 and 50 years after the start of the mining operation the bowl substantially increases in extent due to the fact that the cavern field is developing into the western direction (compare Enclosures 11 and 12). 50 years after the start of the mining operation the subsidence rates are higher in the centre of the bowl (8 mm/year vs. 5 mm/year) and the area affected by rates of 1 mm/year is larger compared to the case when 12 caverns are taken into account.

5.2 Results of Base Case Scenario

As a consequence of the reduction of the convergence rates in Scenario 2, the predicted subsidence is smaller. For example, the maximum subsidence after 50 years of brine production from 12 caverns is about 25 cm compared with 34 cm for the Worst Case Scenario (Table 6). The same relation is correct for the maximum displacement rate in the centre of the bowl (3 mm/year vs. 5 mm/year after 50 years).

The subsidence bowls calculated for Scenario 2 and Scenario 3 are not principally different in extent. This means that the area affected by subsidence is only slightly smaller for the Base Case Scenario (Scenario 3) compared to the Worst Case Scenario (Scenario 2).

Table 6: **Scenario 3** – Increase of subsidence with time in the centre of the subsidence bowl

Time after Start of Production [years]	**Maximum Subsidence in the Centre of the Bowl (12 Caverns) [m]**	**Maximum Subsidence in the Centre of the Bowl (36 Caverns) [m]**
20	0.15	0.16
50	0.25	0.33

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Appendix A

Basic description of the applied Sroka/Schober Model

Formulae used by the applied Sroka/Schober subsidence prediction model which has been selected in the SaltSubsid code are presented in the following. A general visualization of the subsidence trough is given in Enclosure A.1.

Applied formulas for subsidence prediction according to Sroka und Schober (1982)

$$s(r,t) = a \cdot f(r,t) \cdot V_C(t)$$

Equation A.1

with

$s(r,t)$	value of surface subsidence with regard to location r and time t
a	bulking factor
$f(r,t)$	shape function of the subsidence bowl on surface
$V_C(t)$	convergence volume (volume losses) with regard to time
r	radius from cavern axis according to equation A.3
t	time

Simplified shape function of subsidence bowl

$$f(r) = \frac{1}{R^2} \cdot e^{\left(-\pi\left(\frac{r}{R}\right)^2\right)}$$

Equation A.2

with

R	representative maximum radius of the subsidence bowl (see equation A4)
r	radius from cavern axis according to equation A.3

Identification of surface point with regard to cavern axis

$$r = \sqrt{(x - x_K)^2 + (y - y_K)^2}$$

Equation A.3

with

x_k, y_k	coordinates of cavern axis in ground map view

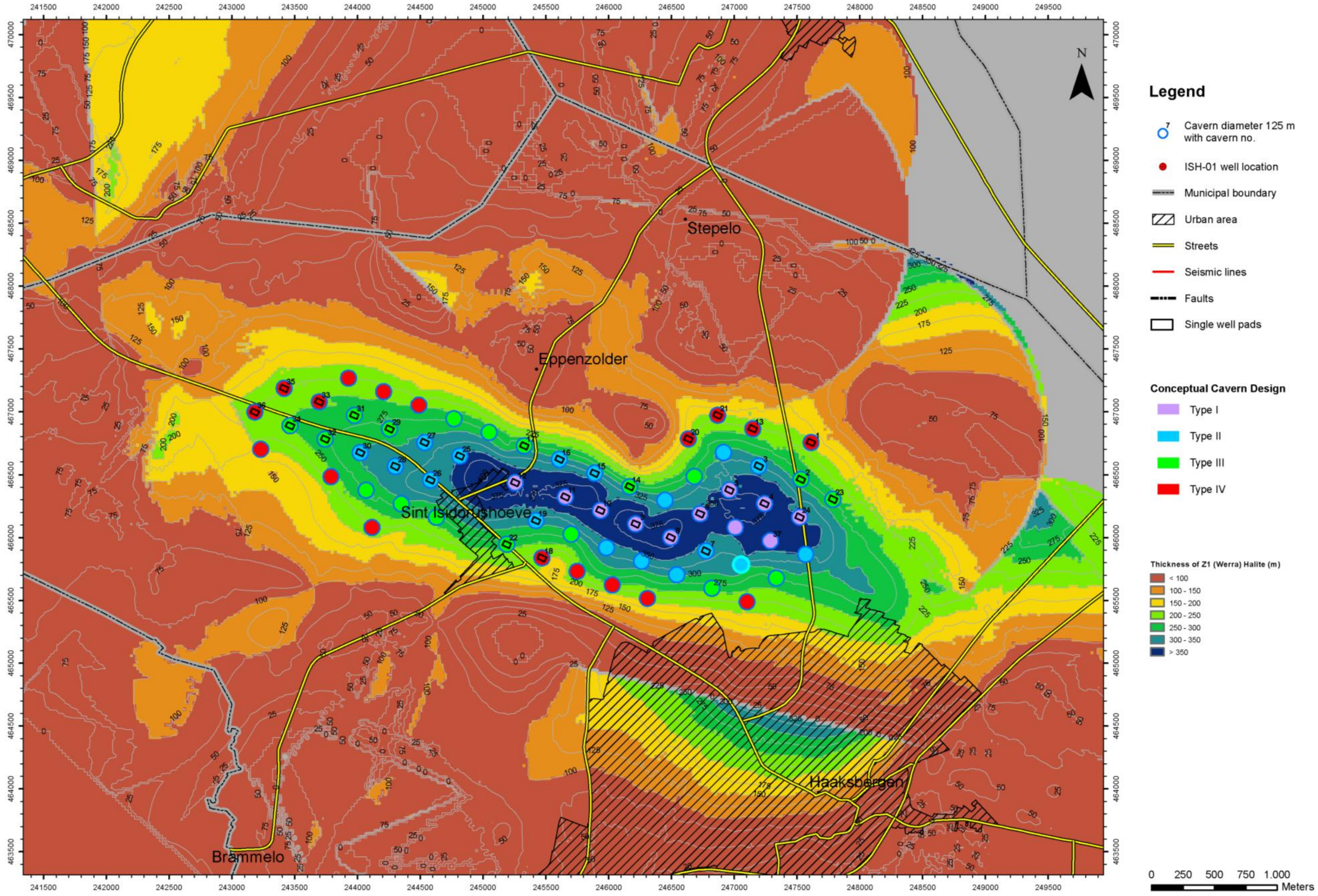
Definition of representative maximum radius of volume convergence

$$R = \frac{\sqrt{z_u \cdot z_o}}{\tan \beta}$$ Equation A.4

with

R	representative maximum radius of the subsidence bowl
z_u	depth of deepest point of the cavern
z_o	depth of cavern roof
β	angle of draw

The above given formulae cover the calculation of subsidence generated by a single cavern, whereas in reality several caverns will be developed. Thus, the subsidence troughs of all caverns have to be superimposed.



Enclosure 1

Haaksbergen – Cavern field layout based on to the leaching concept of DEEP. 2012

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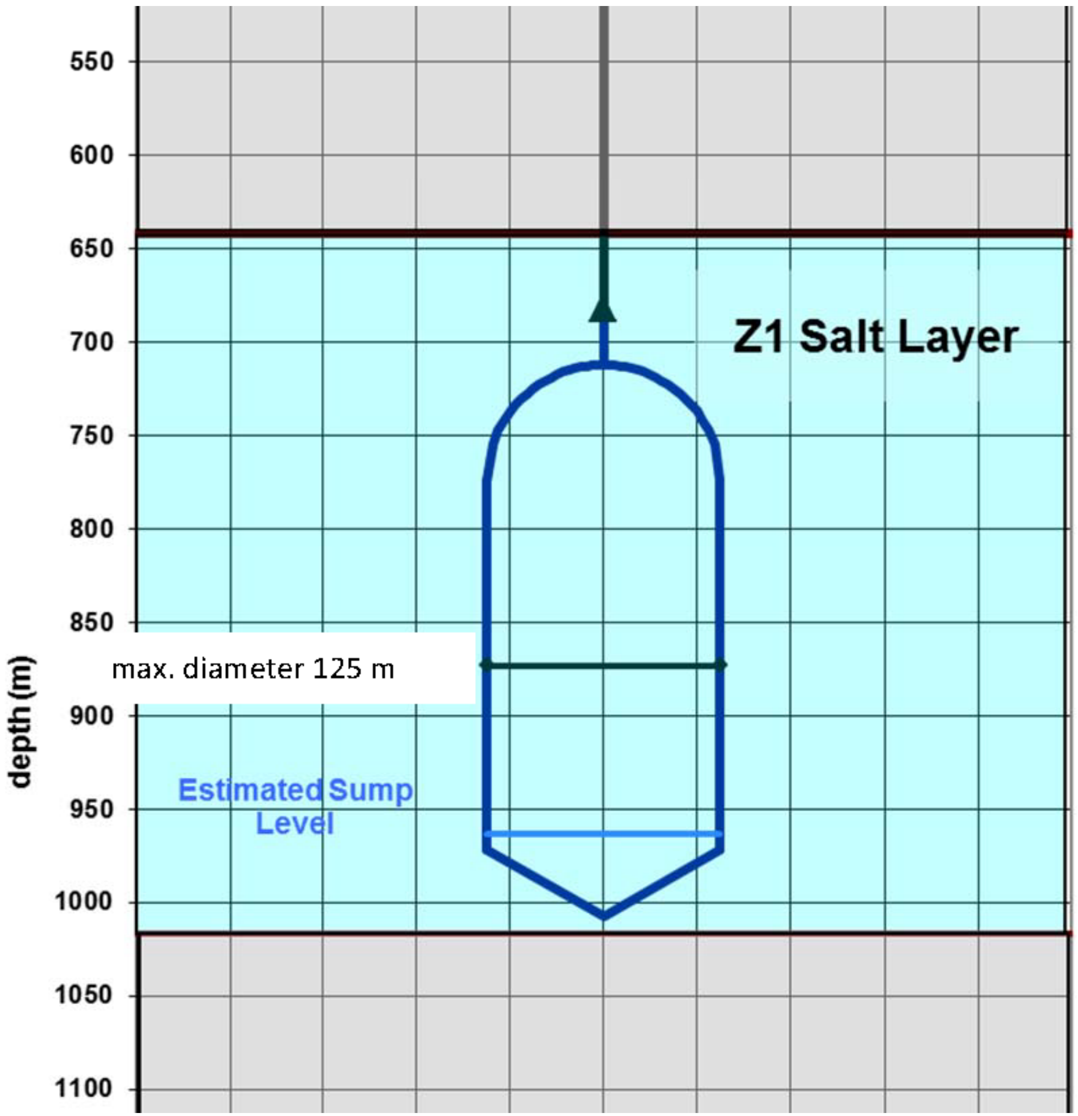
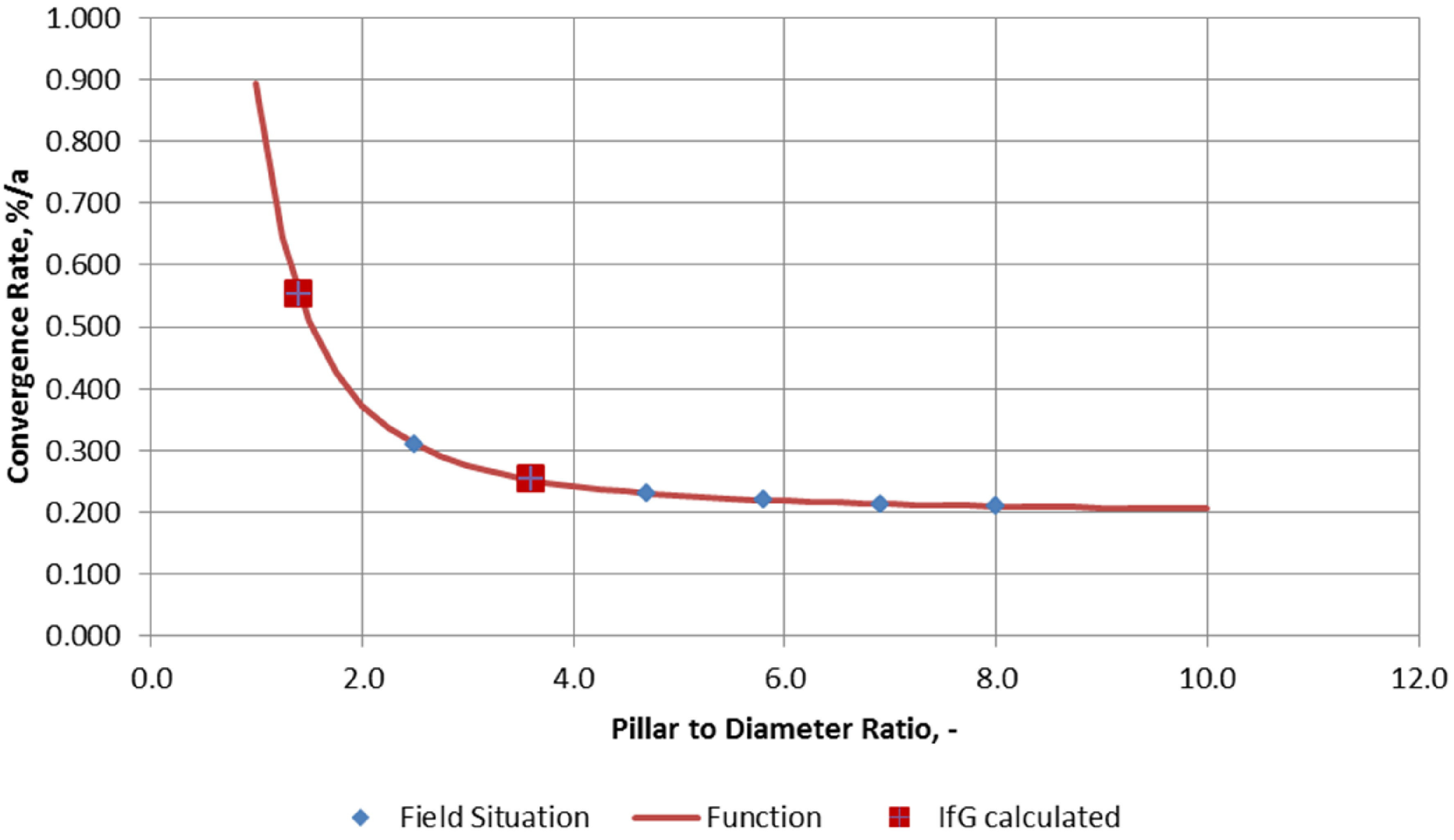


- 642.0 m (top of salt)
- 682.0 m (CS)
- 712.0 m (roof)
- 774.5 m (top cyl.)
- 972.0 m (bottom cyl.)
- 1007.0 m (sump)
- 1017.0 m (base of salt

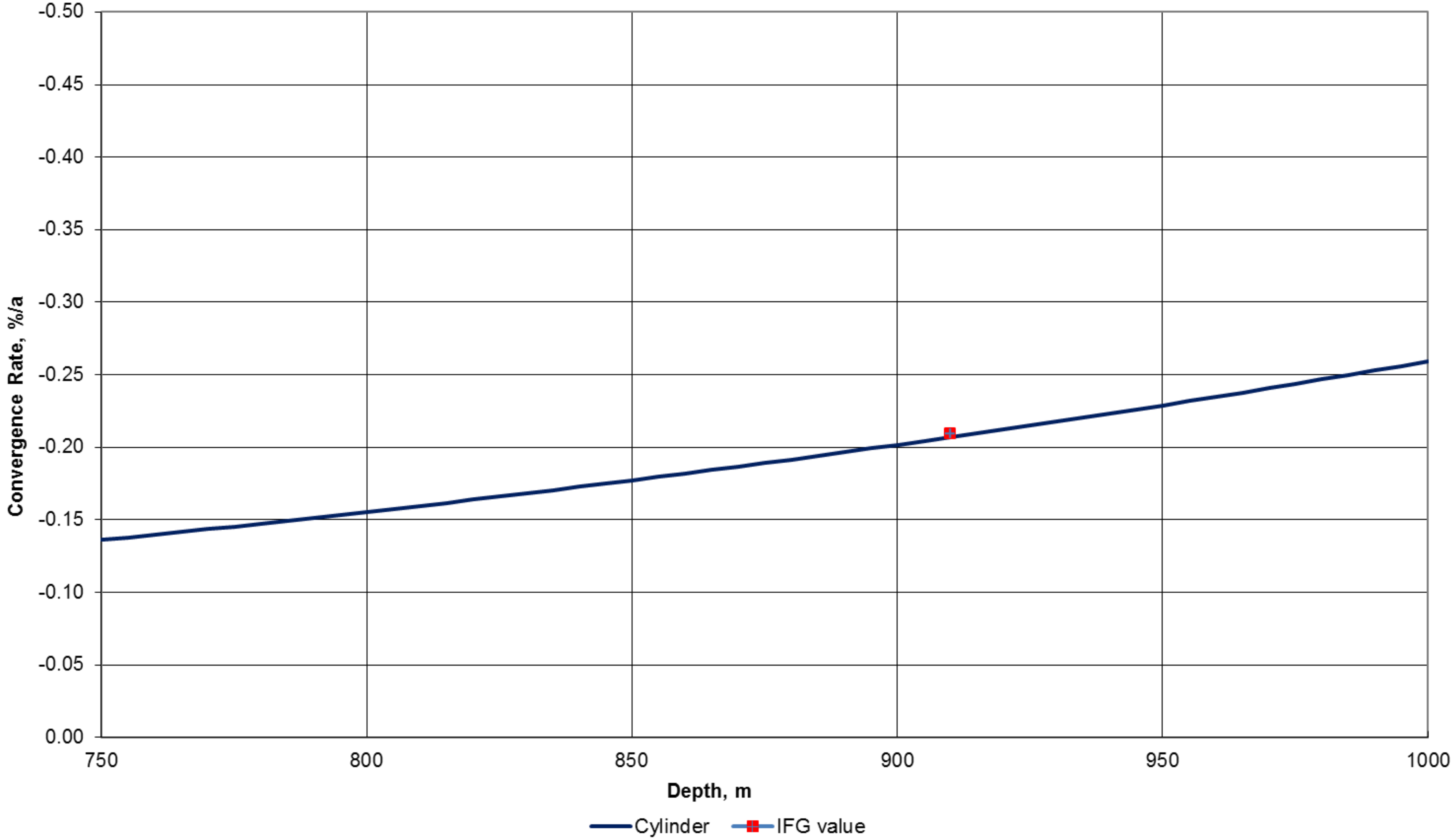
Enclosure 2

Haaksbergen – Limiting parameters for the rock mechanical envelope



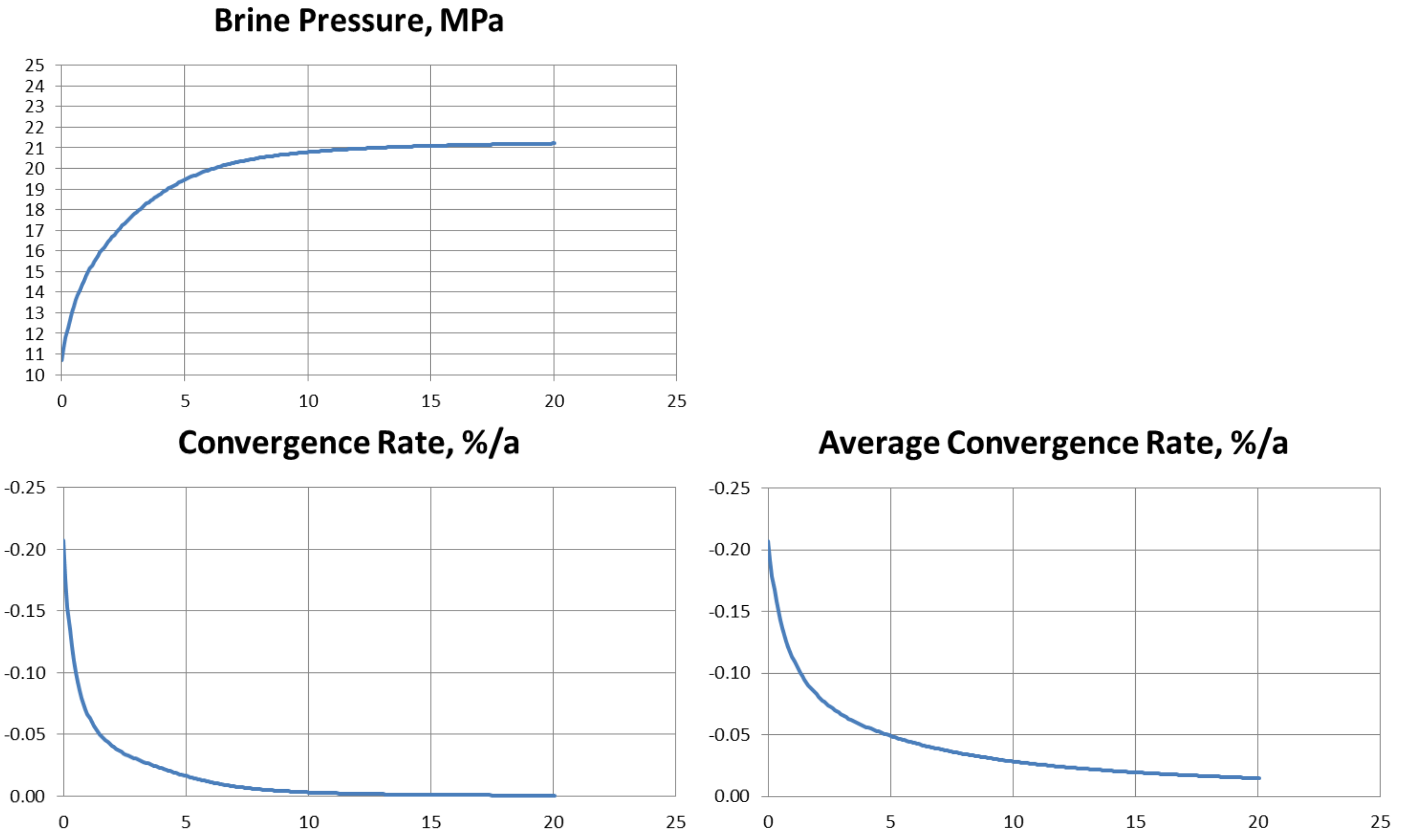
Enclosure 3

Haaksbergen – Convergence rate with regard to salt pillar to cavern diameter ratio



Enclosure 4

Haaksbergen – Creep response versus depth applying analytical formula of v. Sambeek (1993)



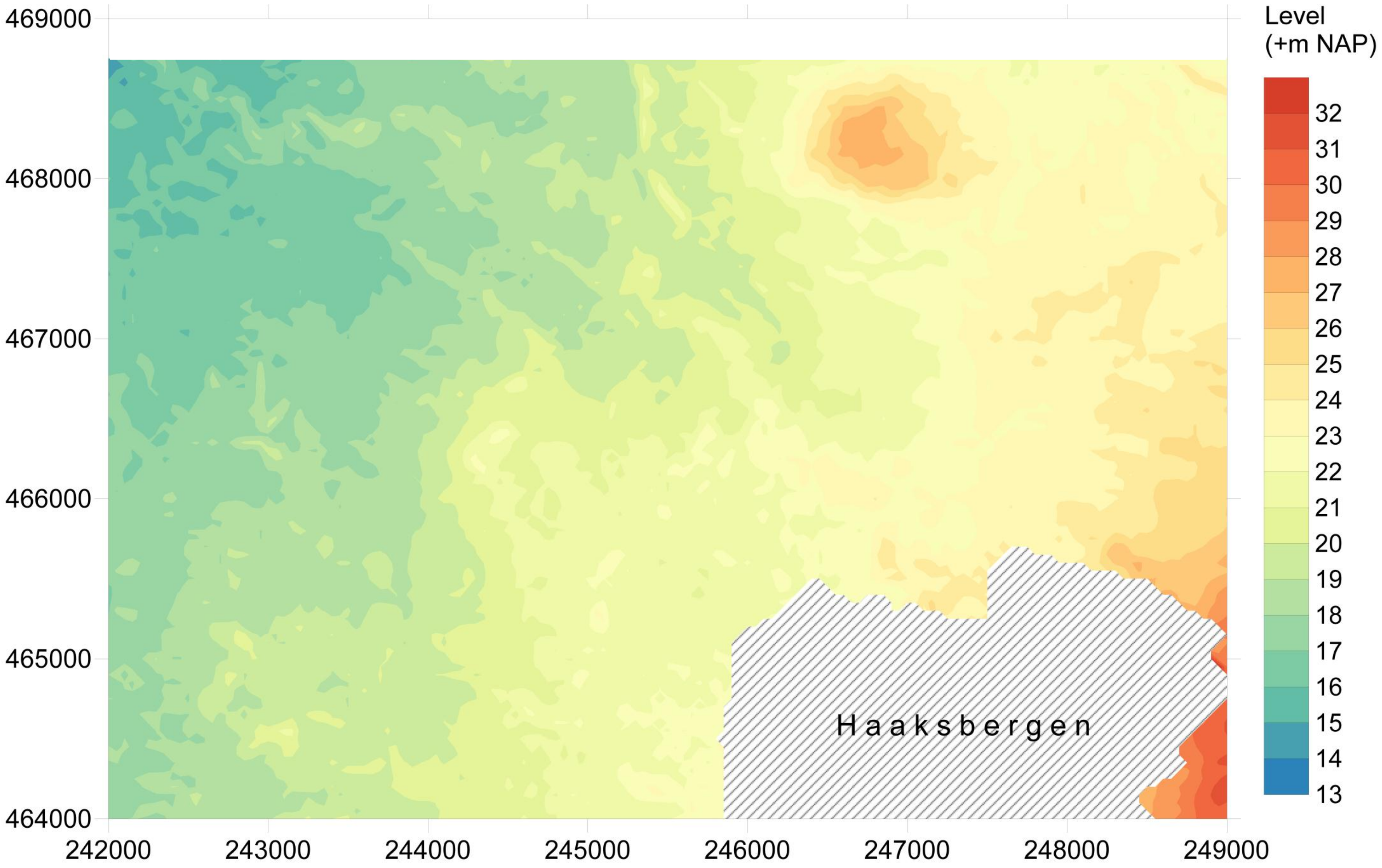
Brine Pressure, MPa

Convergence Rate, %/a

Average Convergence Rate, %/a

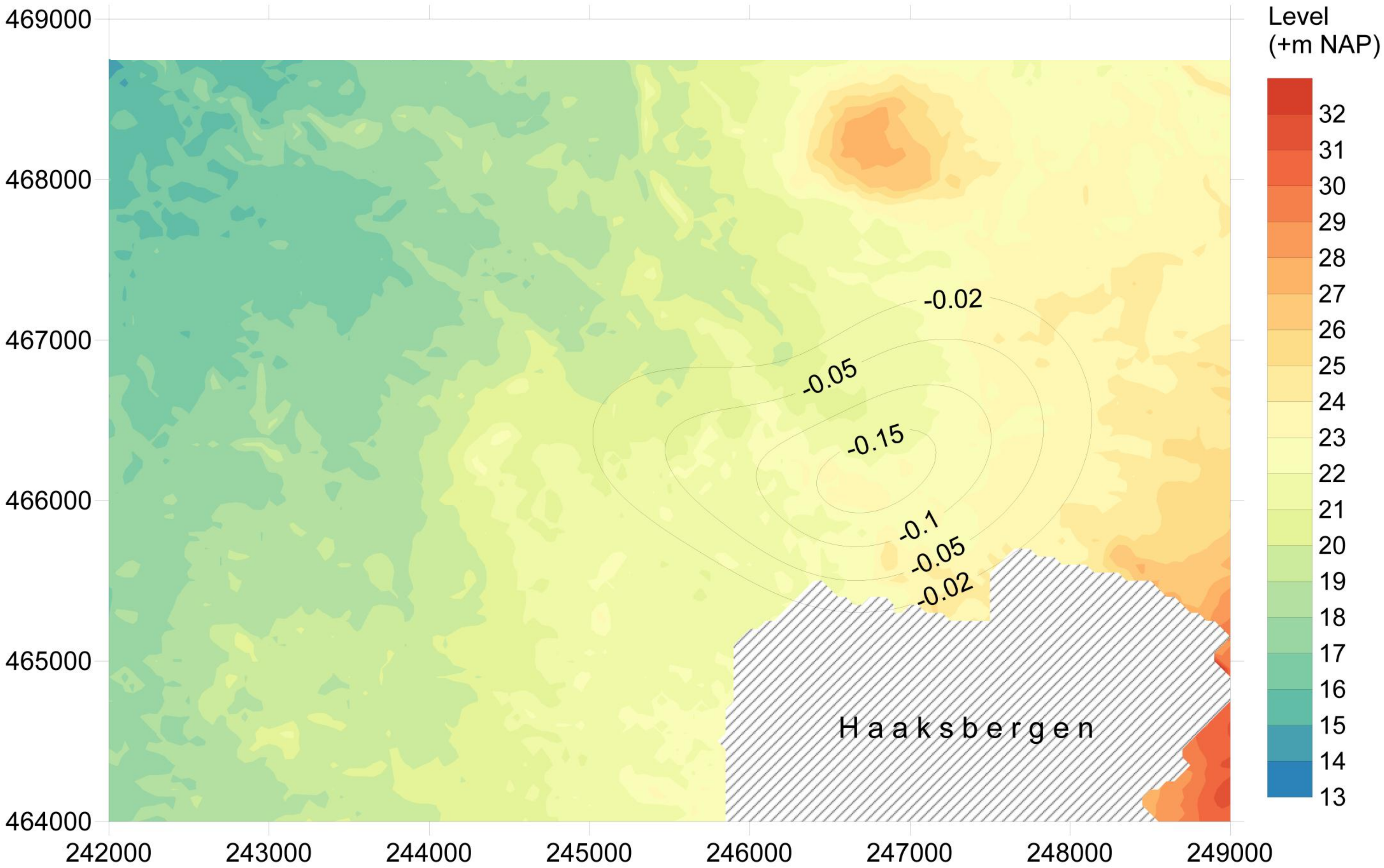
Enclosure 5

Haaksbergen – Estimate of pressure and convergence rate after plugging



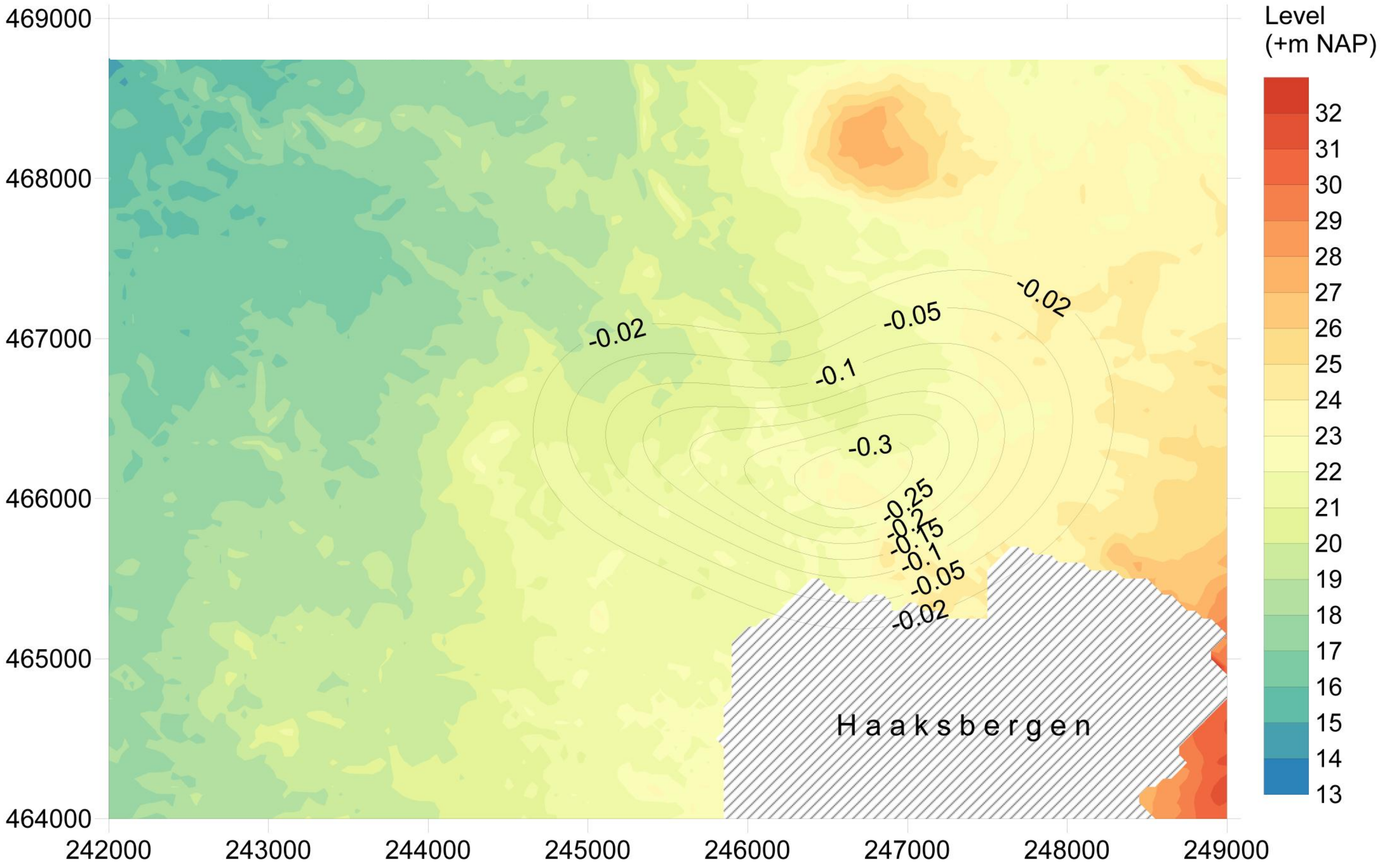
Enclosure 6

Haaksbergen – Basic topographic map of the cavern area



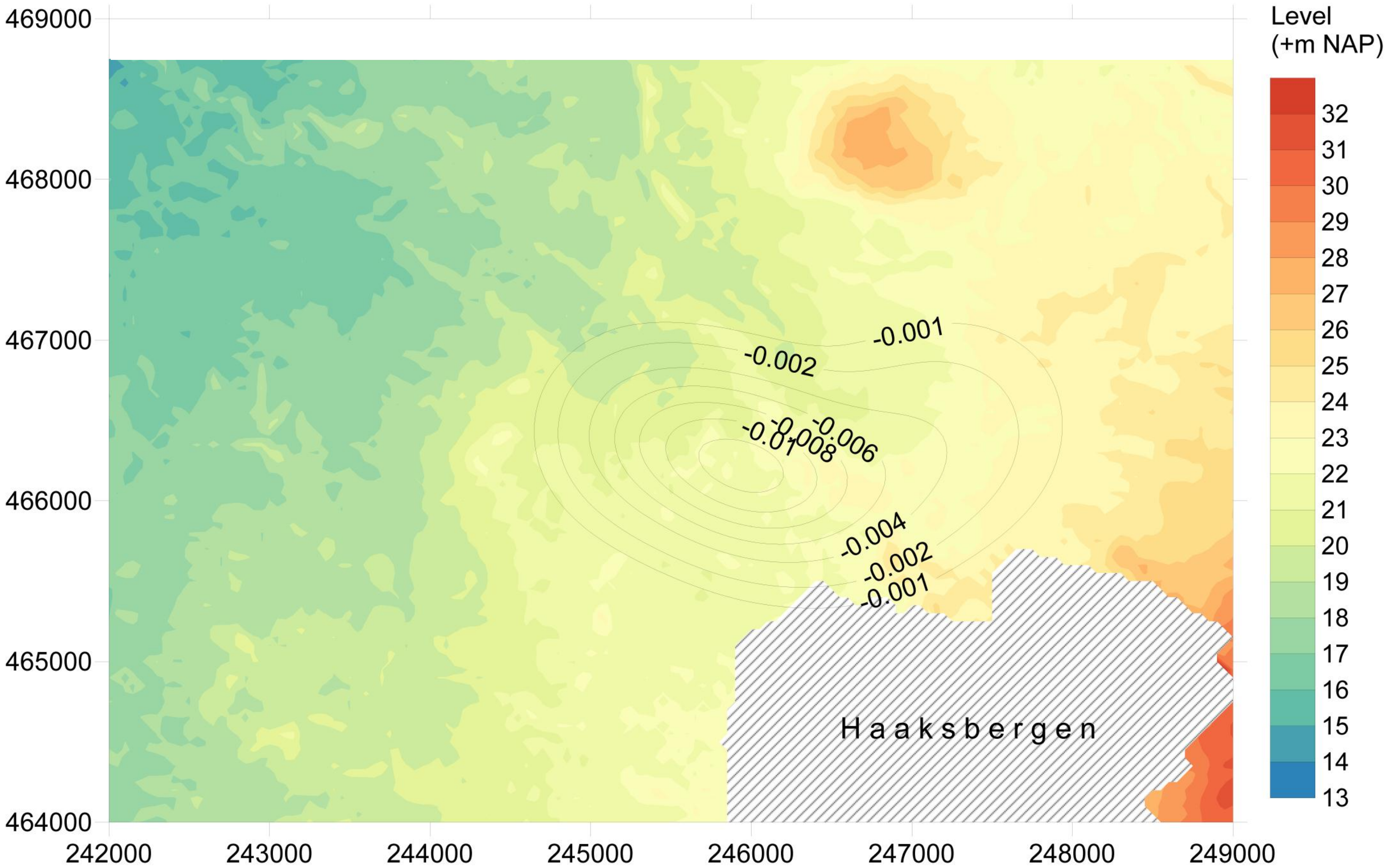
Enclosure 7

Haaksbergen – Scenario 2 (12 Caverns) – Subsidence map – 20 years after start of leaching



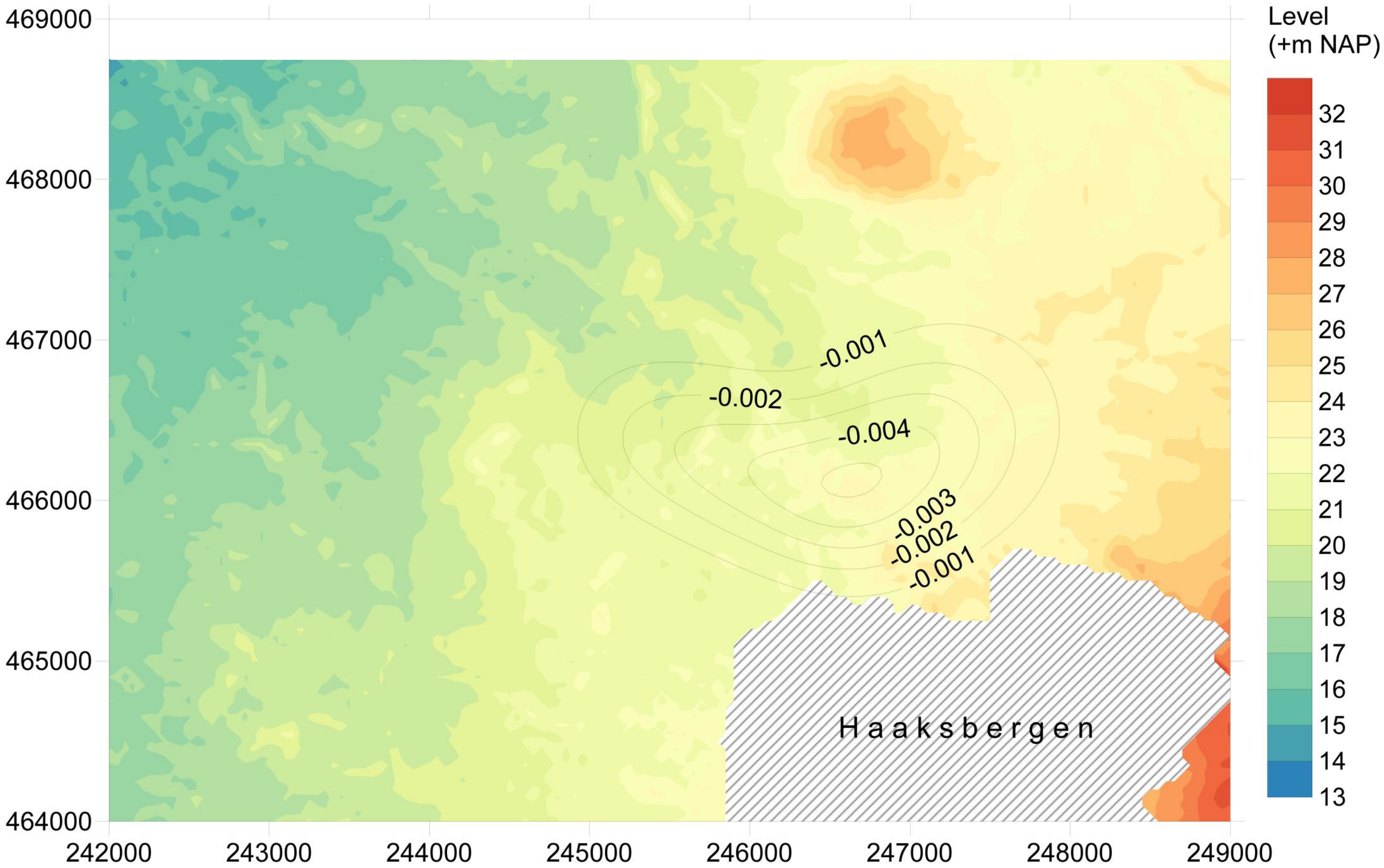
Enclosure 8

Haaksbergen – Scenario 2 (12 Caverns) – Subsidence map – 50 years after start of leaching



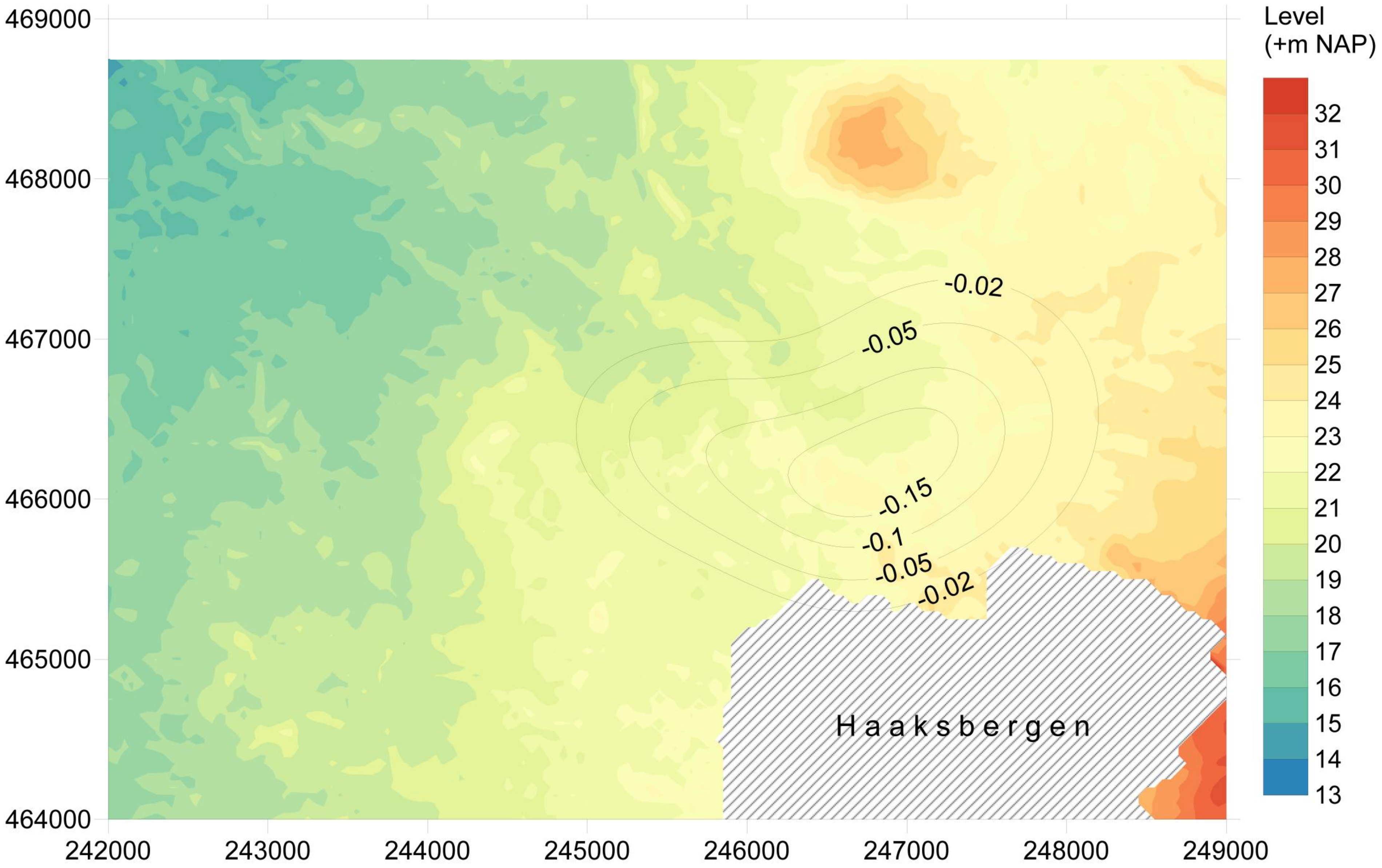
Enclosure 9

Haaksbergen – Scenario 2 (12 Caverns) – Displacement rates – 20 years after start of leaching



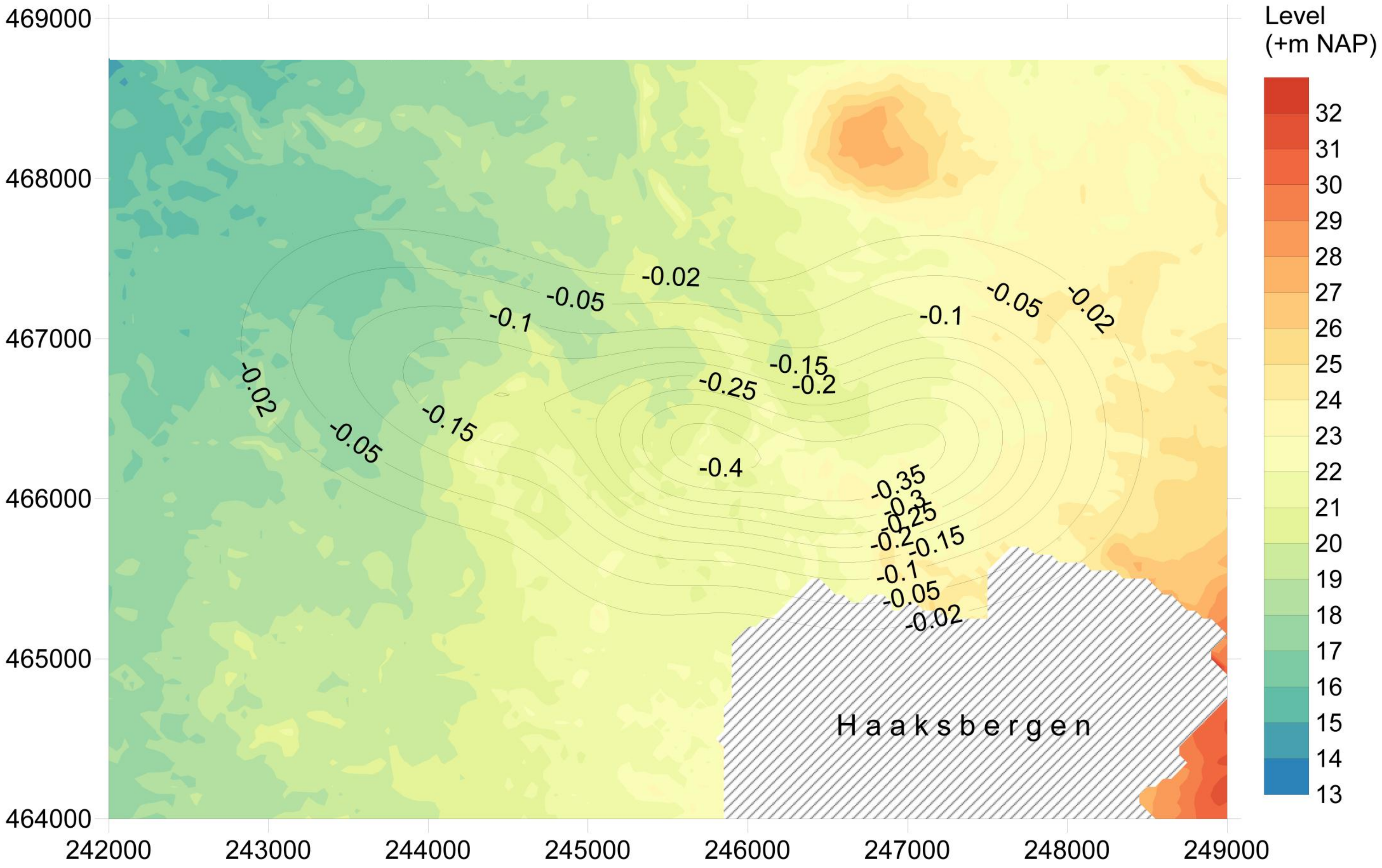
Enclosure 10

Haaksbergen – Scenario 2 (12 Caverns) – Displacement rates – 50 years after start of leaching



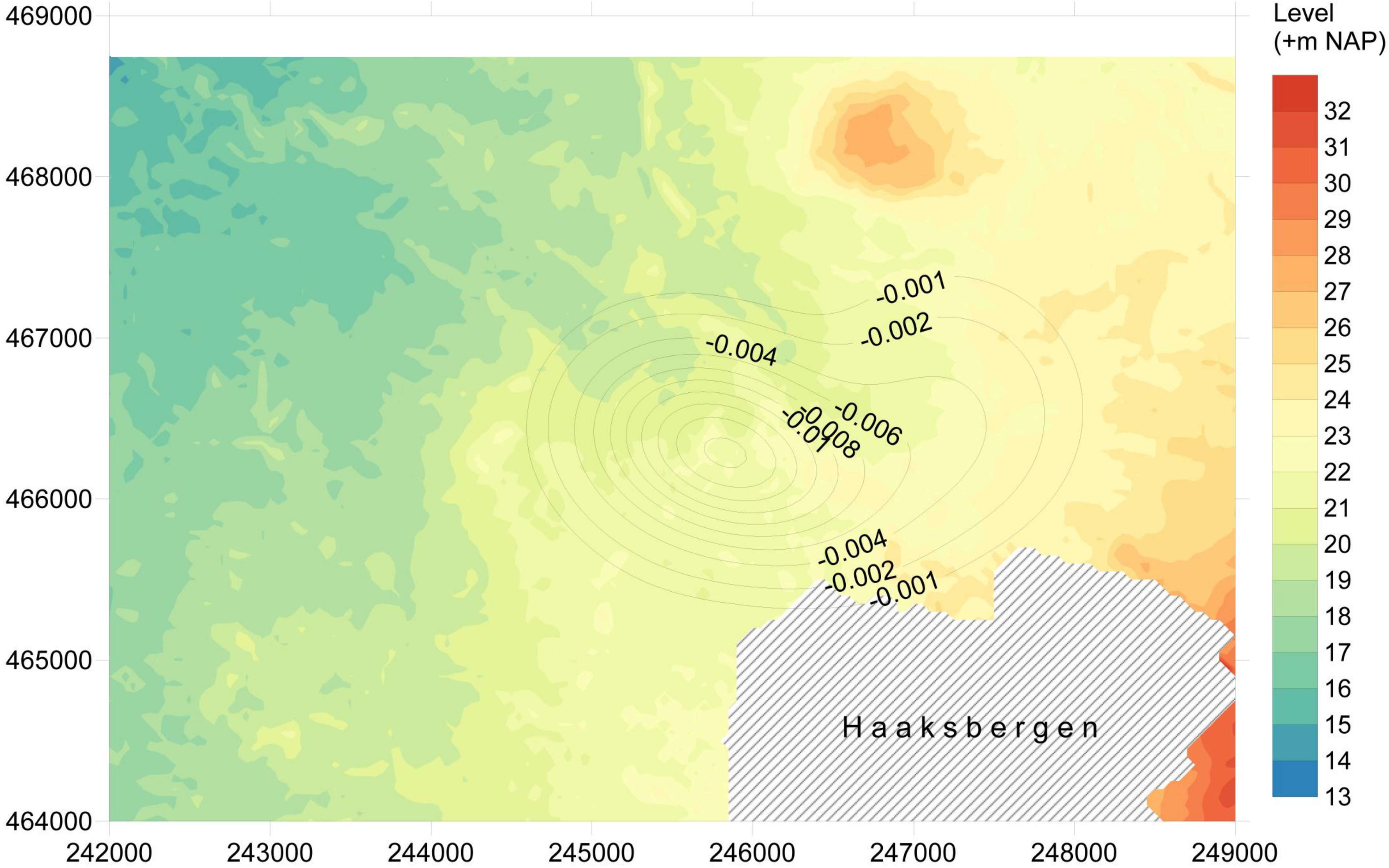
Enclosure 11

Haaksbergen – Scenario 2 (36 Caverns) – Subsidence map – 20 years after start of leaching



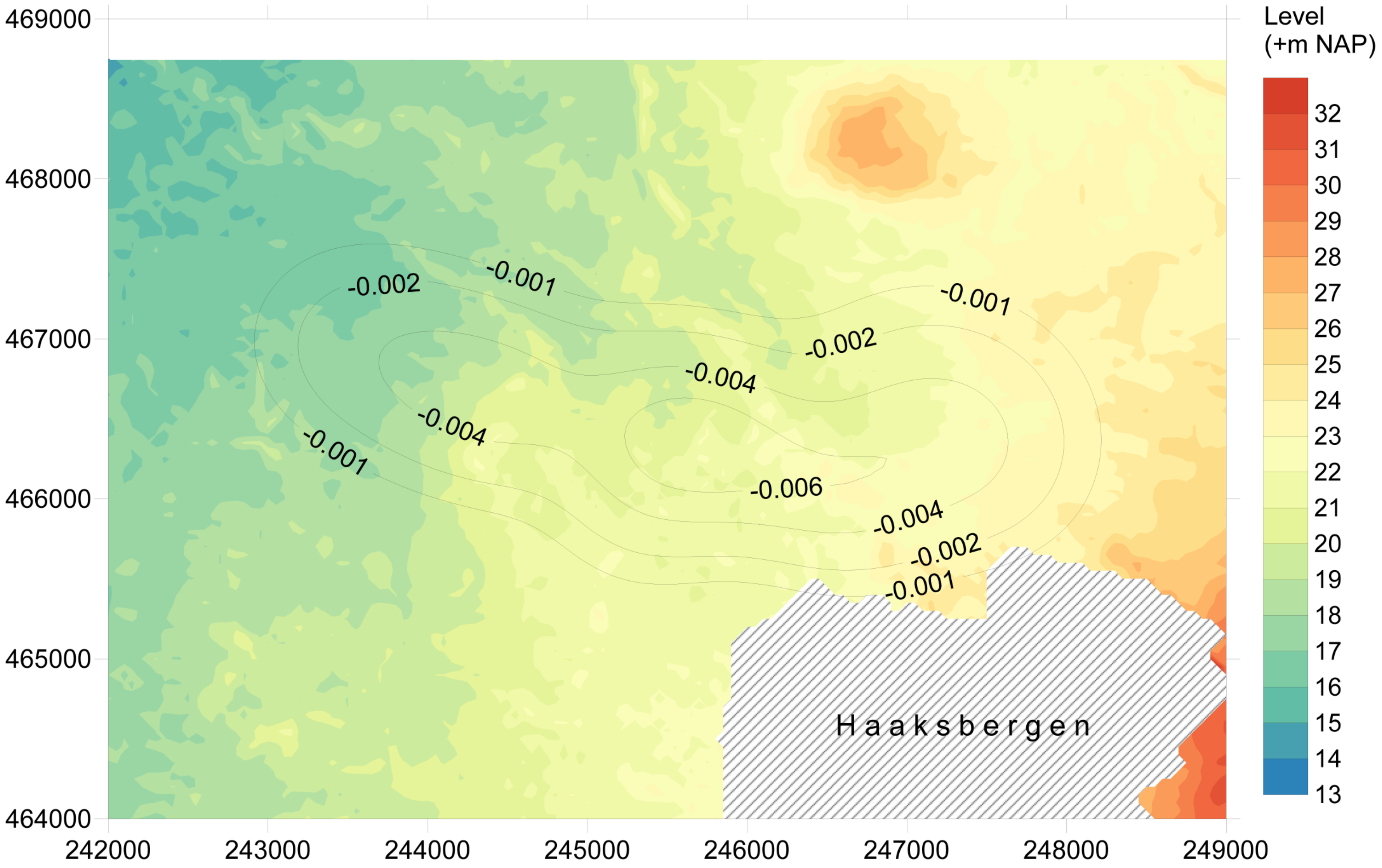
Enclosure 12

Haaksbergen – Scenario 2 (36 Caverns) – Subsidence map – 50 years after start of leaching



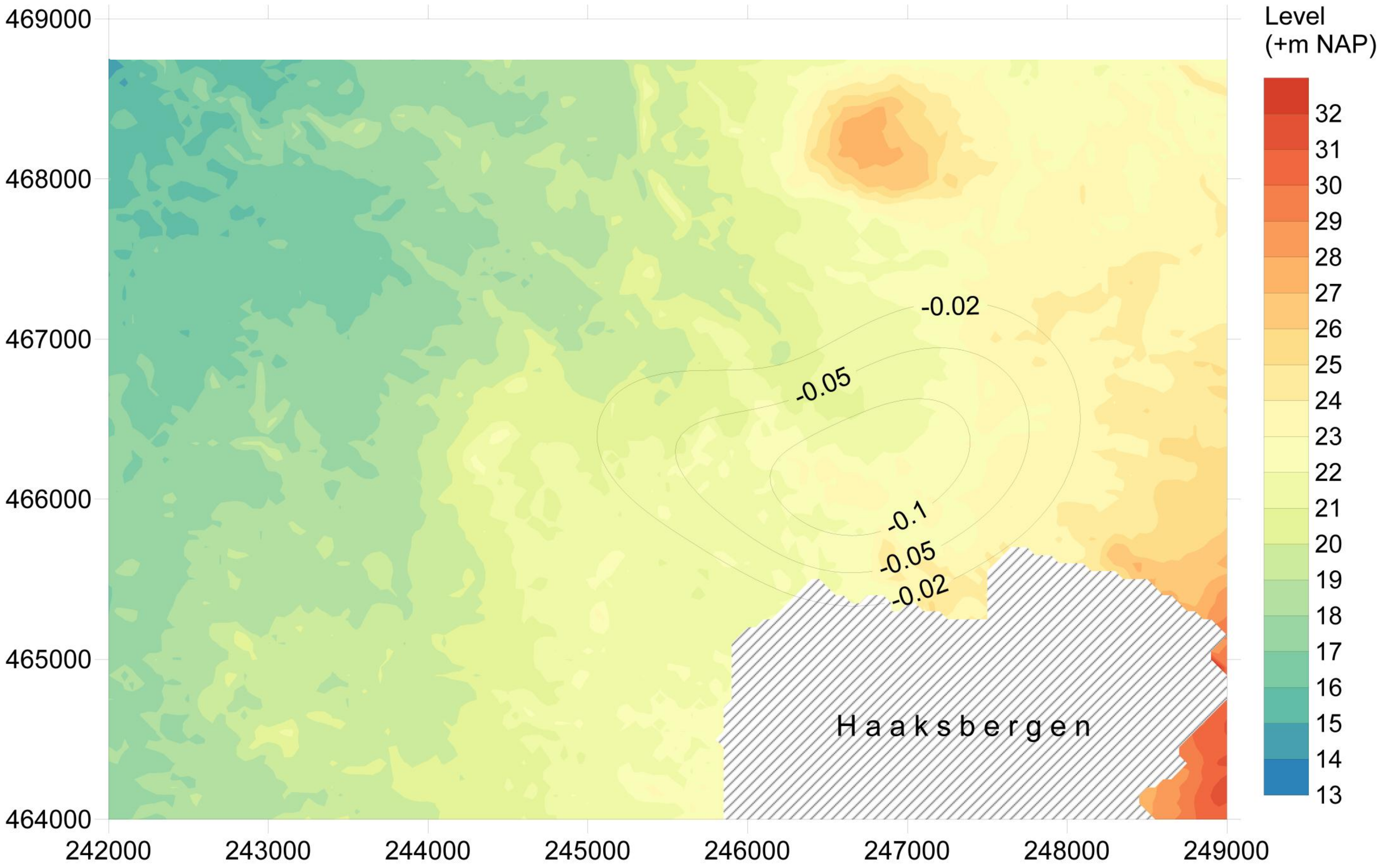
Enclosure 13

Haaksbergen – Scenario 2 (36 Caverns) – Displacement rates – 20 years after start of leaching



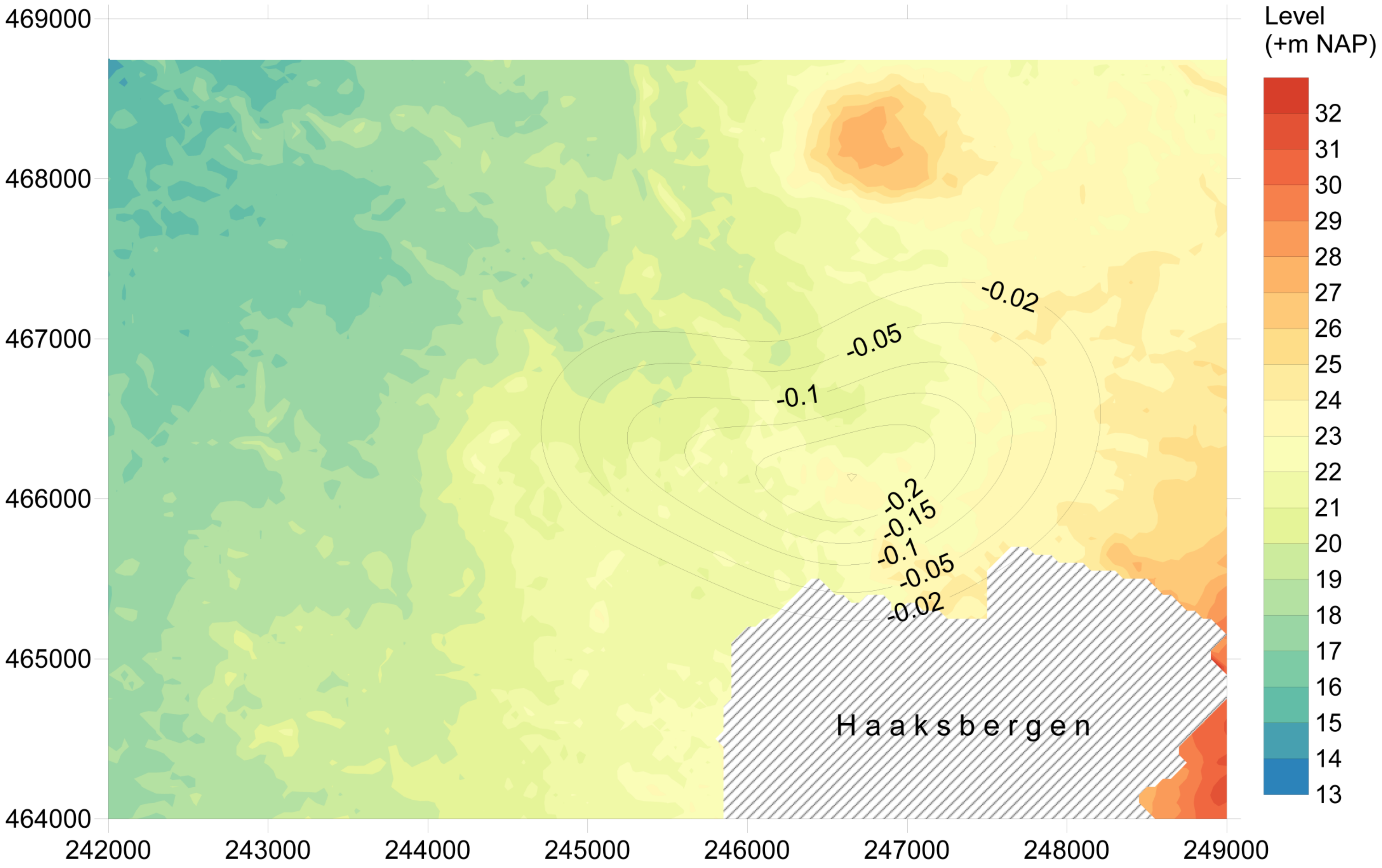
Enclosure 14

Haaksbergen – Scenario 2 (36 Caverns) – Displacement rates – 50 years after start of leaching



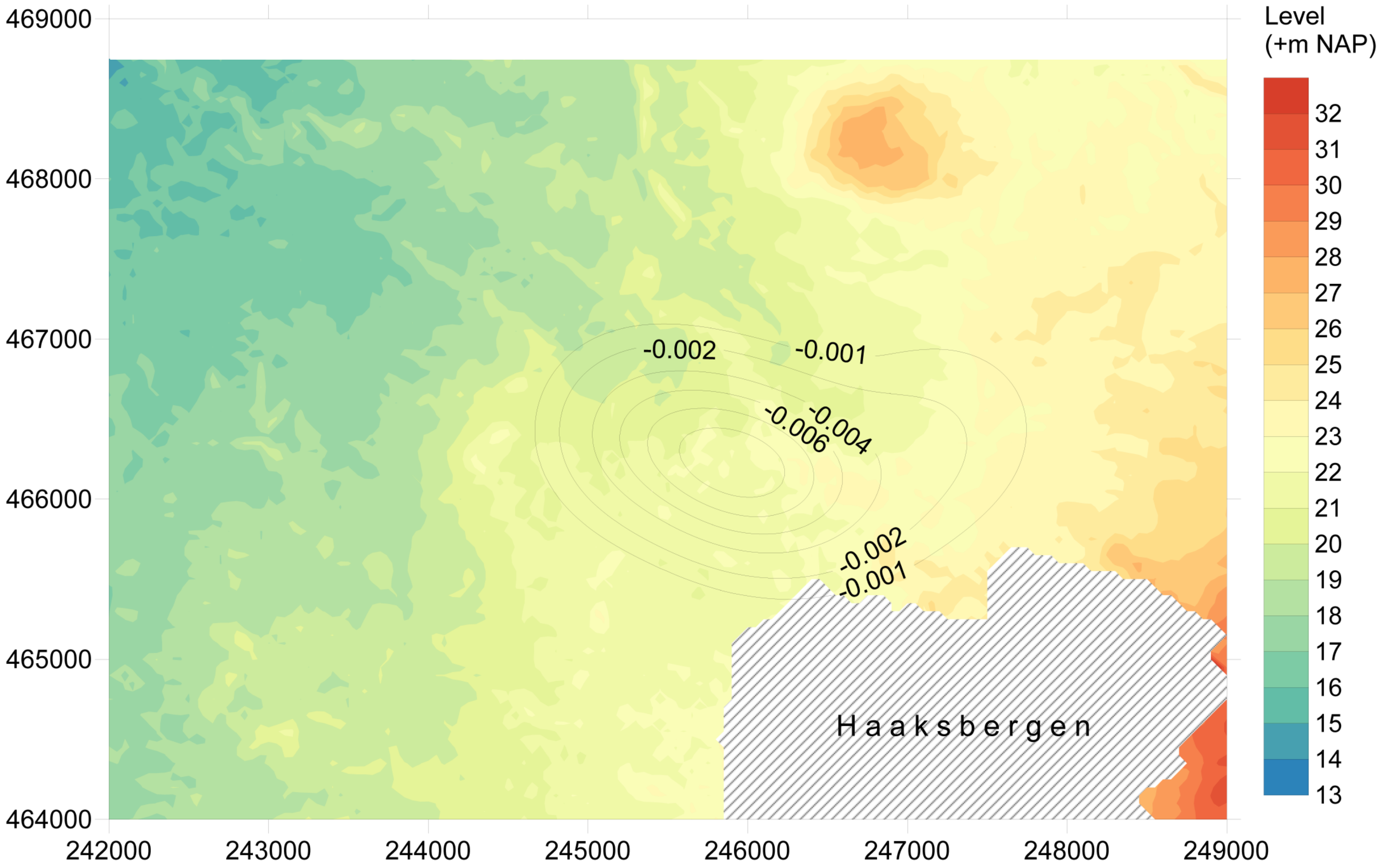
Enclosure 15

Haaksbergen – Scenario 3 (12 Caverns) – Subsidence map – 20 years after start of leaching



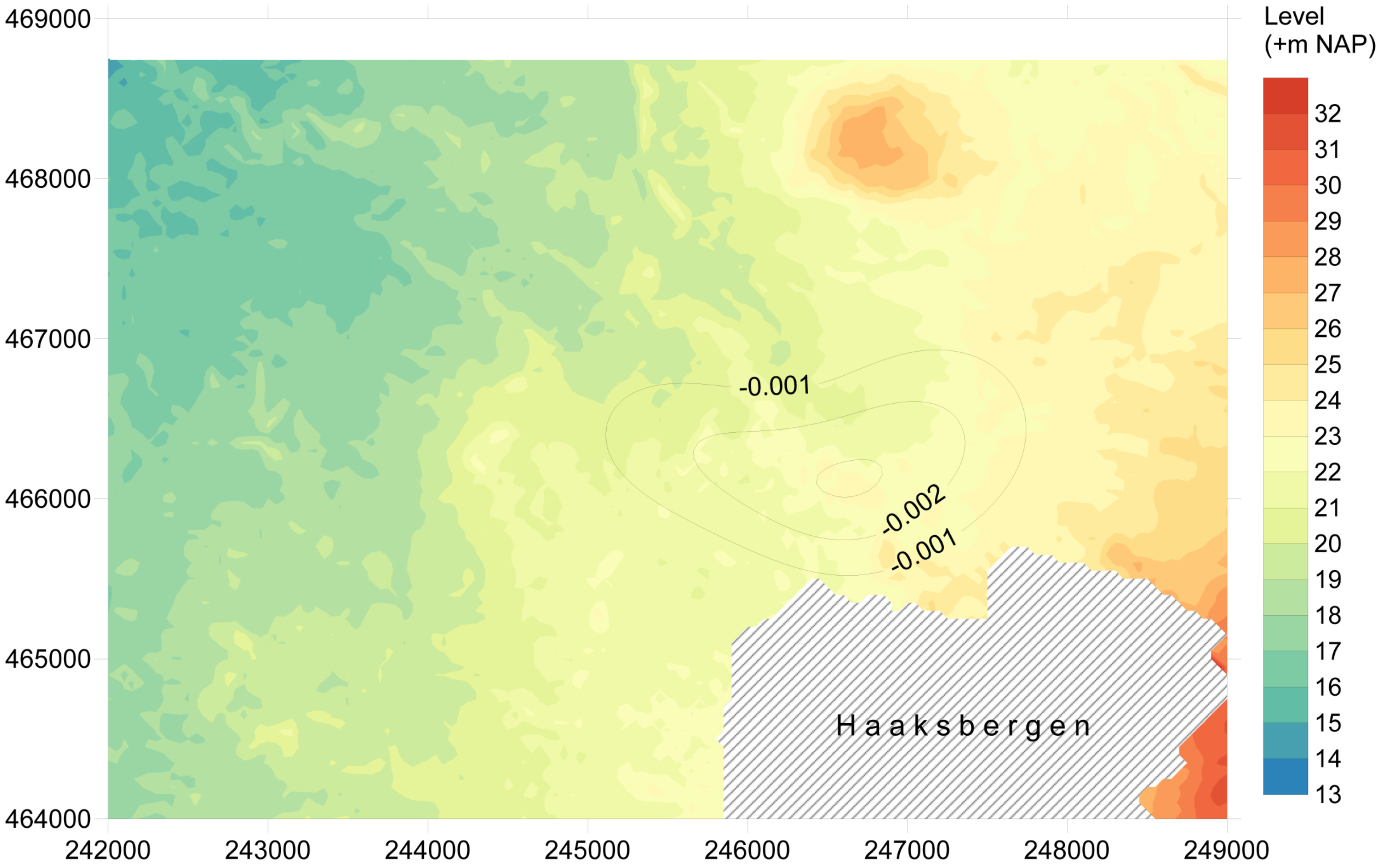
Enclosure 16

Haaksbergen – Scenario 3 (12 Caverns) – Subsidence map – 50 years after start of leaching



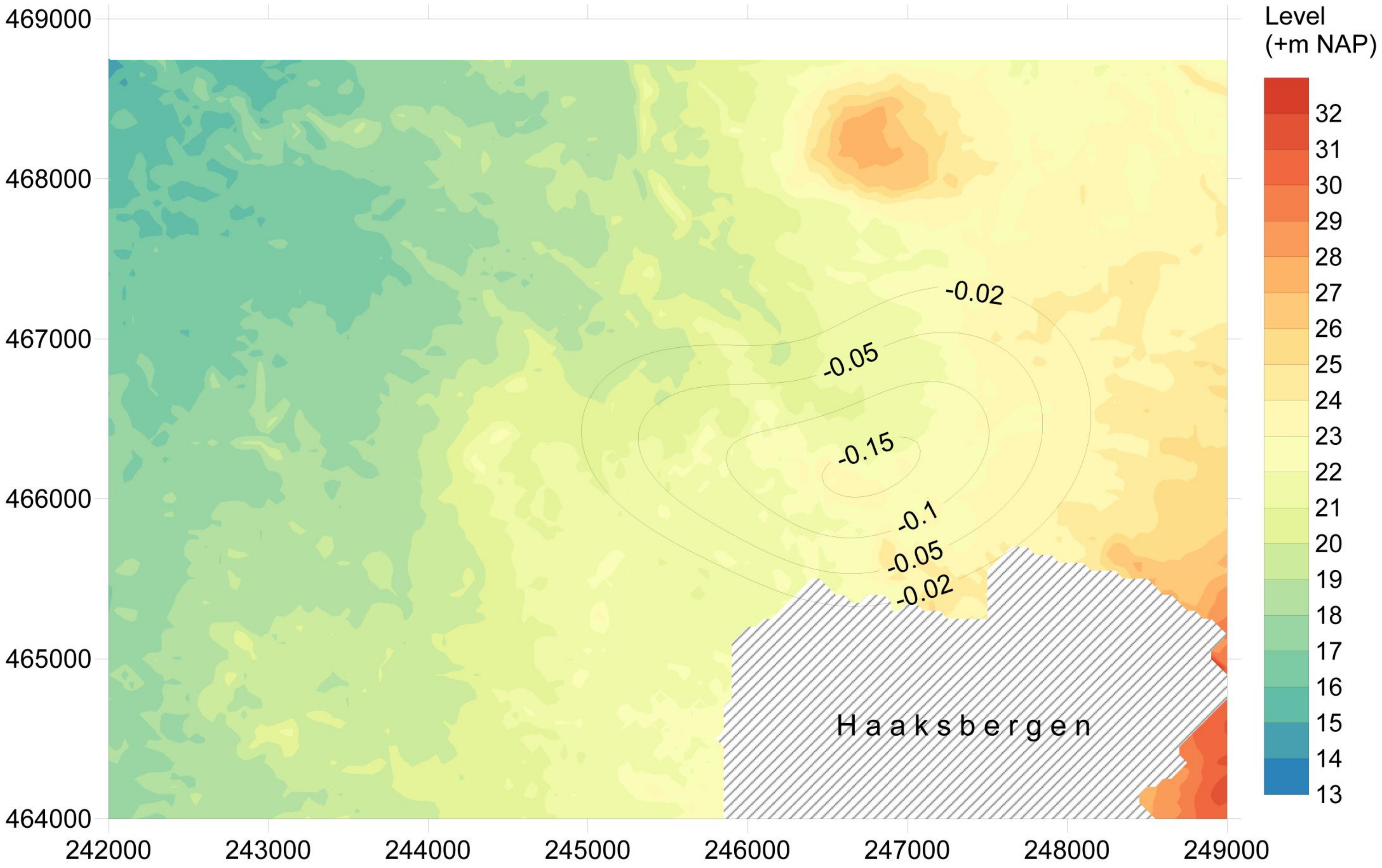
Enclosure 17

Haaksbergen – Scenario 3 (12 Caverns) – Displacement rates – 20 years after start of leaching



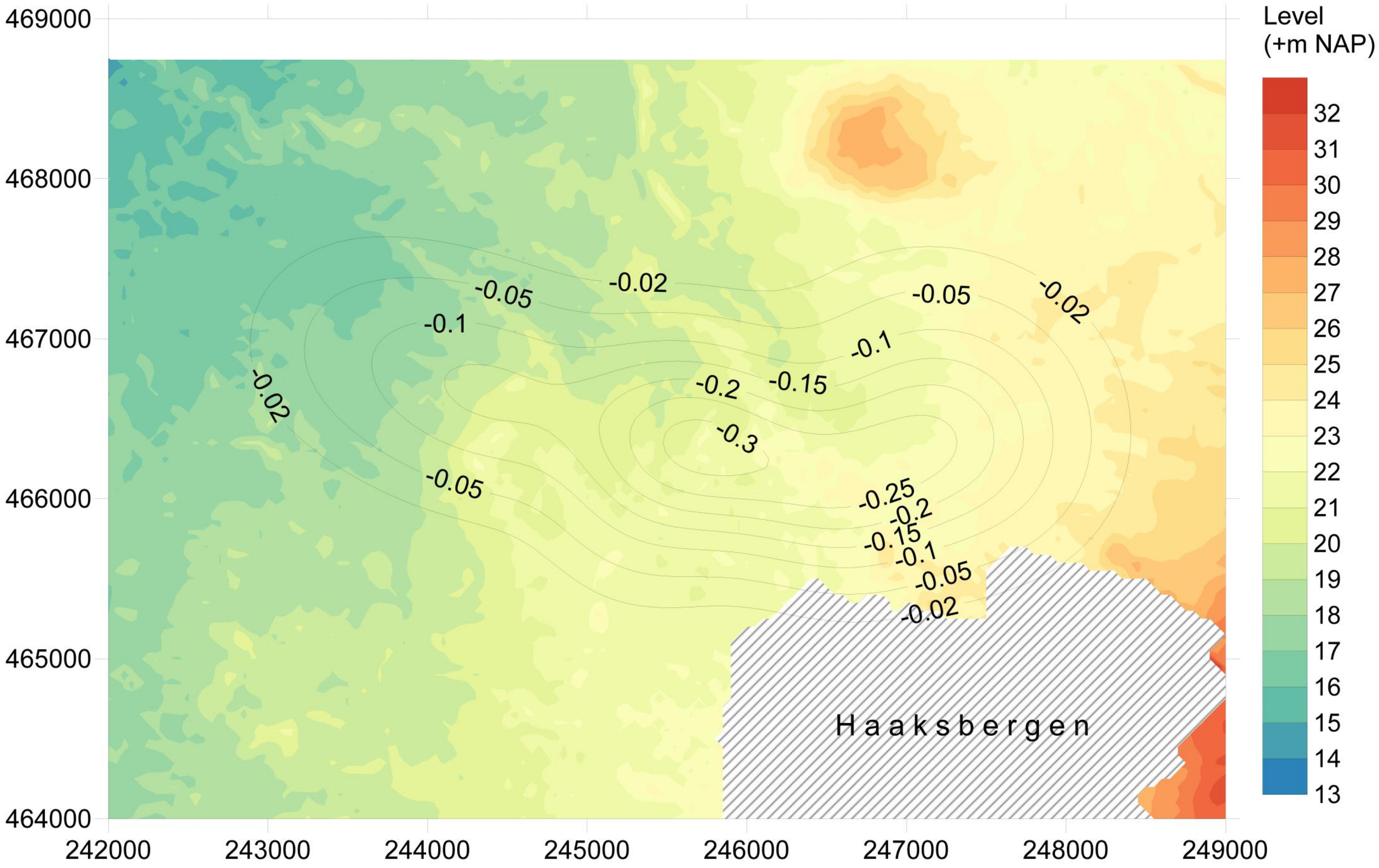
Enclosure 18

Haaksbergen – Scenario 3 (12 Caverns) – Displacement rates – 50 years after start of leaching



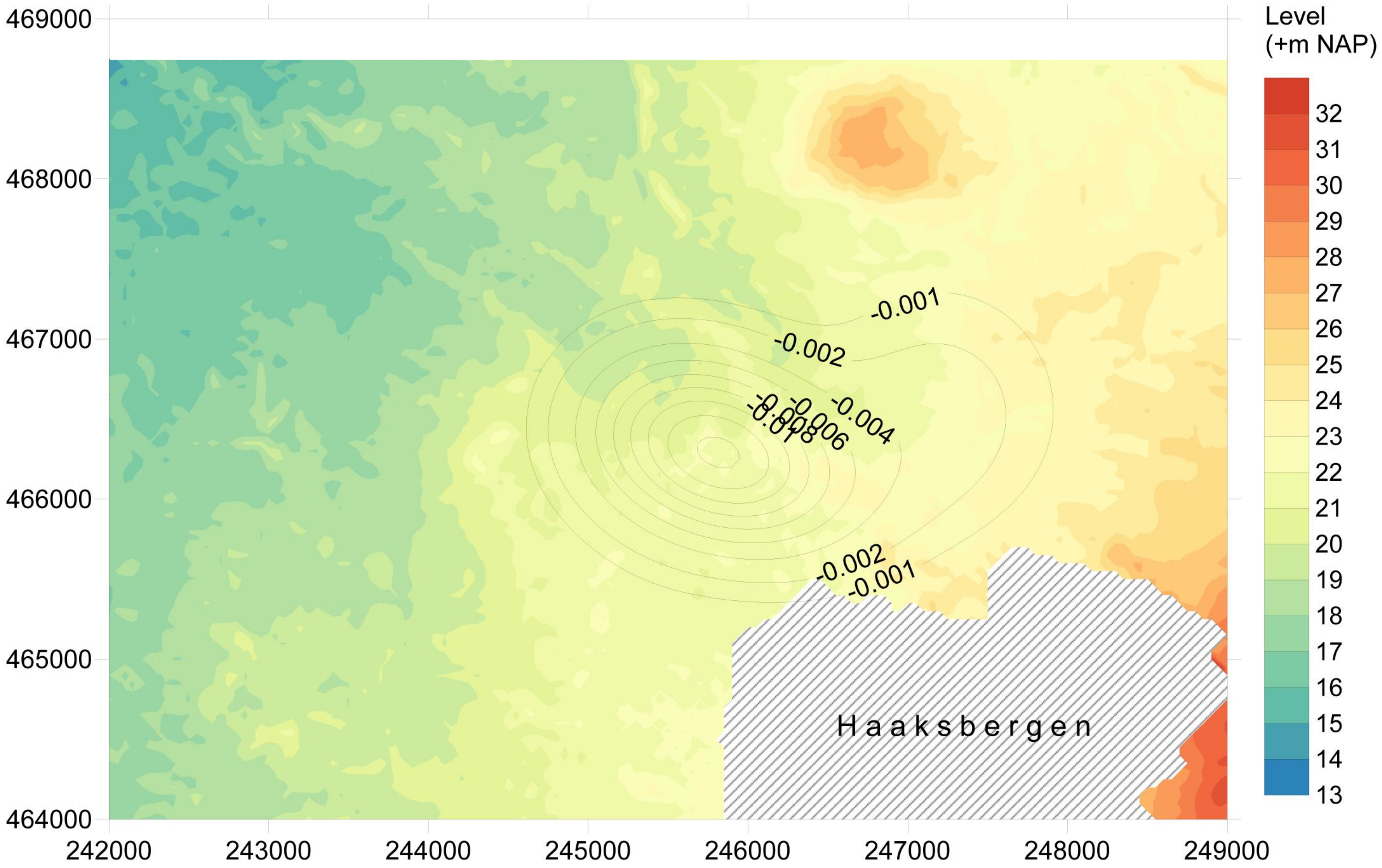
Enclosure 19

Haaksbergen – Scenario 3 (36 Caverns) – Subsidence map – 20 years after start of leaching



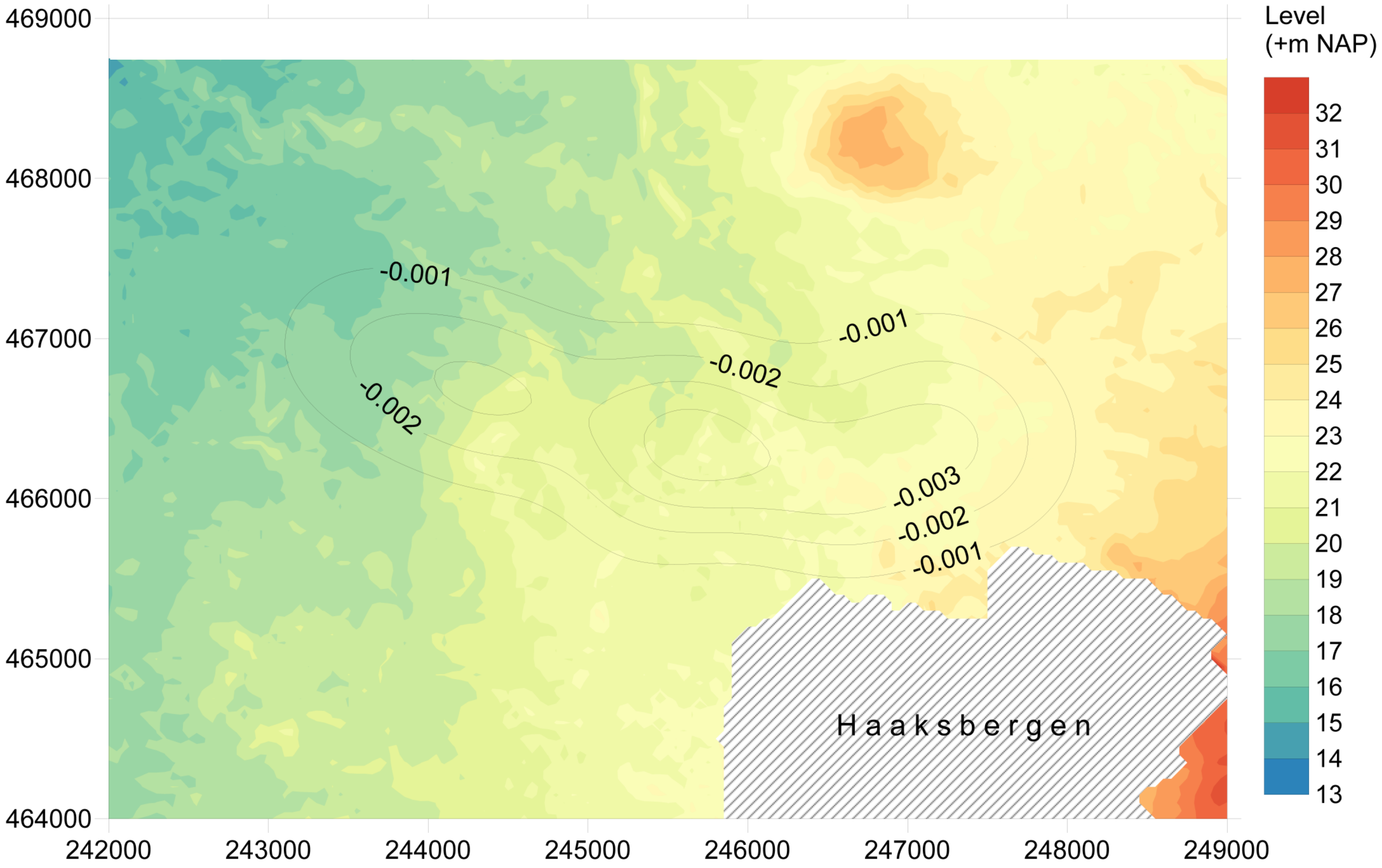
Enclosure 20

Haaksbergen – Scenario 3 (36 Caverns) – Subsidence map – 50 years after start of leaching



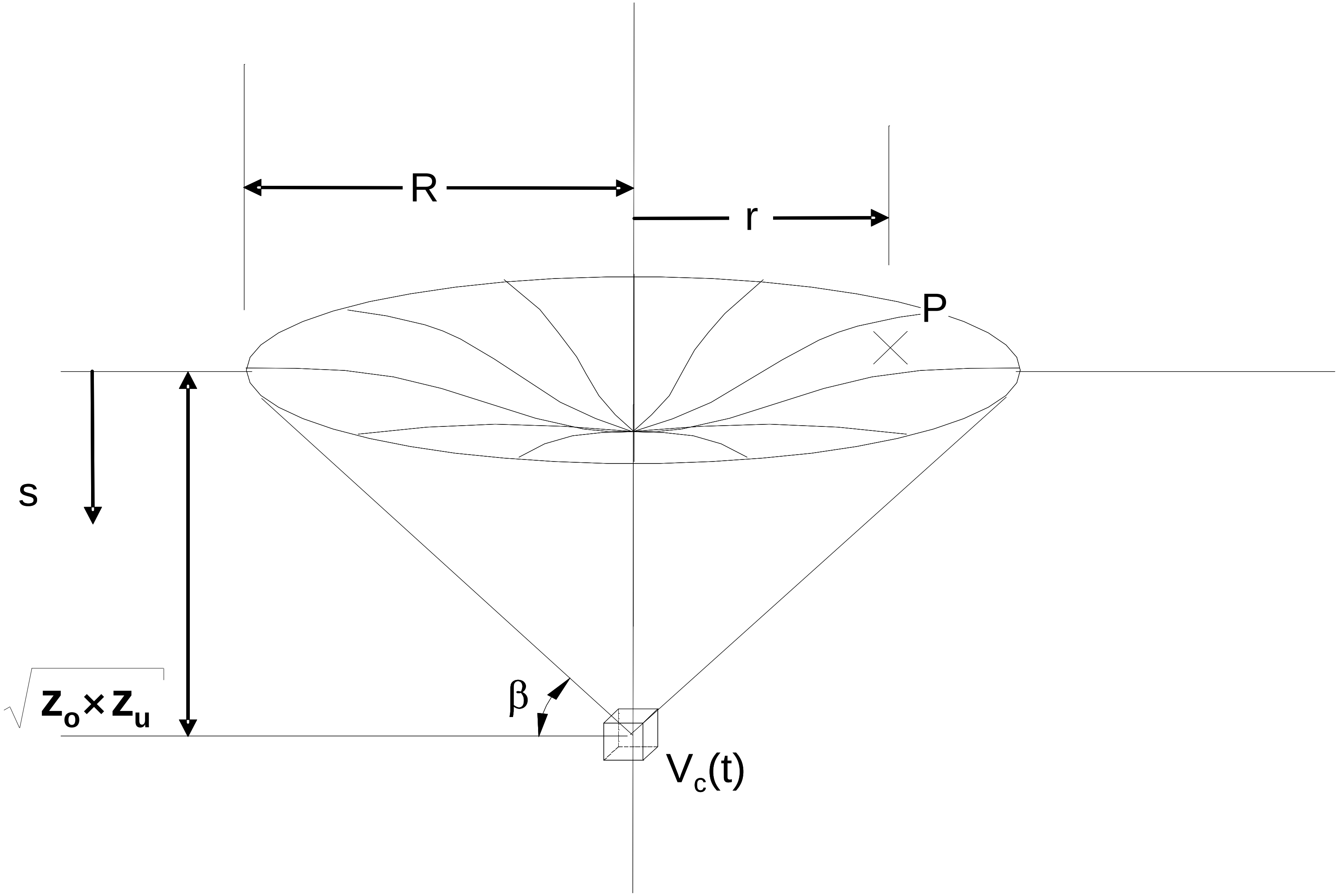
Enclosure 21

Haaksbergen – Scenario 3 (36 Caverns) – Displacement rates – 20 years after start of leaching



Enclosure 22

Haaksbergen – Scenario 3 (36 Caverns) – Displacement rates – 50 years after start of leaching



Enclosure A.1

Subsidence trough at surface due to volume losses at subsurface according to Neuhaus (1976)