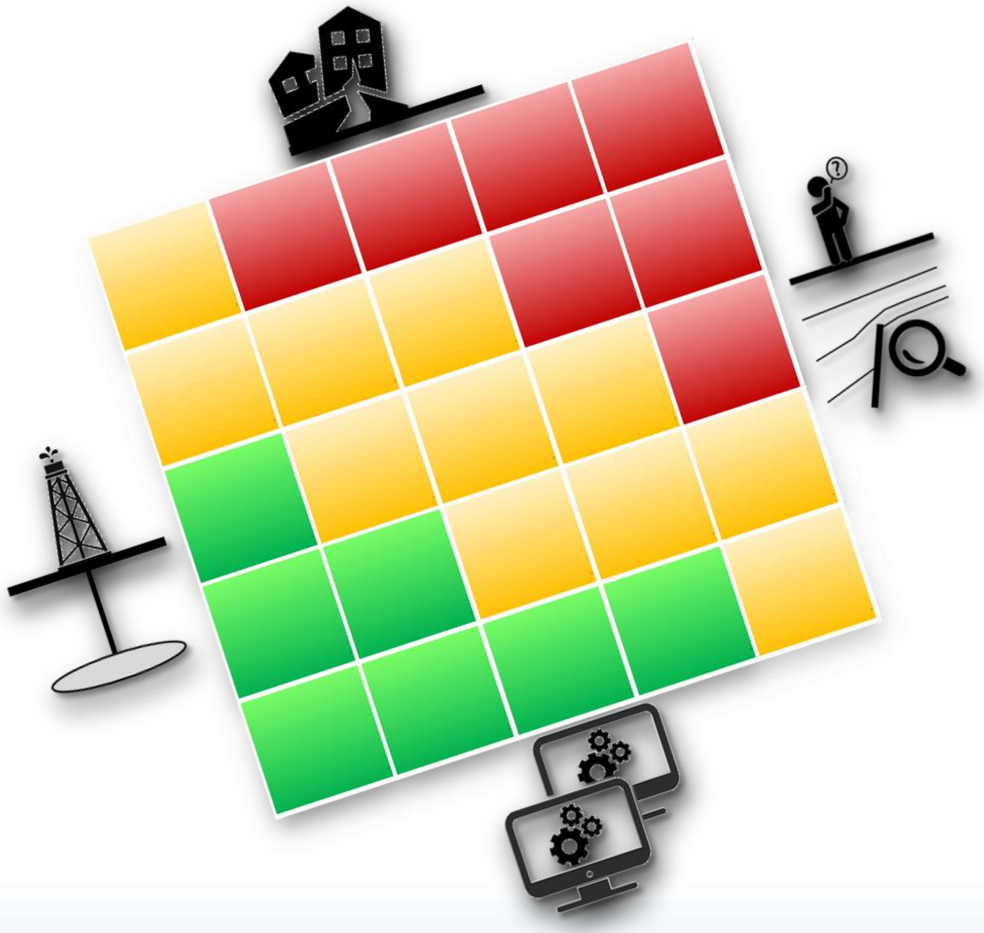
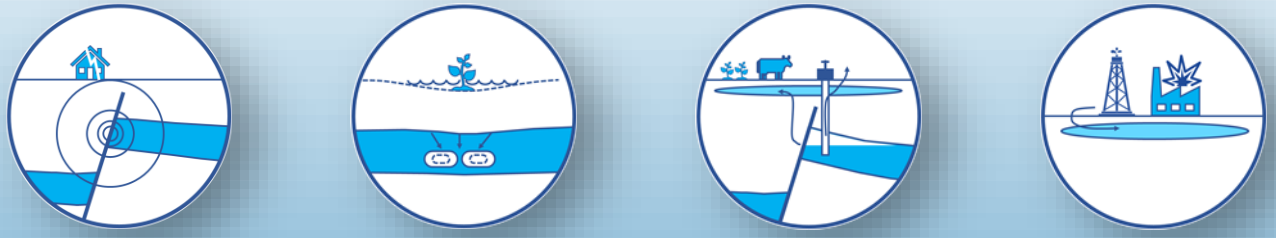
Towards a national research agenda and risk toolbox for mining effects in The Netherlands

A technical reconnaissance





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Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

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TNO report

TNO R10375 | Final report

Towards a National Research Agenda and Risk Toolbox for Mining Effects in The Netherlands

TNO - DELTARES - KNMI

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Summary

Mining activities in the Netherlands remain vital for the supply of energy and to a lesser extend for industrial resources. The main mining activities in the Netherlands, from the present and the past, have been: coal mining, rock salt mining, gas production and storage, oil production, and geothermal energy production. Although gas production - being a dominant mining activity over the past 60 years - steadily declines, there is an expected increase of new and diversifying activities in the Netherlands such as energy production using geothermal sources.

Exploration, production, deployment and abandonment of mining activities may be associated with effects, such as induced seismicity, surface deformation, leakage and facility hazards. Over the past years, risks and impacts from mining effects have resulted in an accelerated increase of societal concerns and anxiety fuelling political debates in the Netherlands.

But risks are not only related to the period of active deployment (e.g. production, storage). Cases such as coal mining in Limburg and salt mining in Twente show that risks can still develop long after the activity has ceased. Over the past decades thousands of deep wells have been drilled and hundreds of salt caverns have been leached. The abandonment of these locations strongly determines the risk from long-term effects (e.g. 500 year forecast on well corrosion and safety).

An adequate management of risks and the reduction of impacts is therefore key to ensure a safe and publicly accepted deployment and development of mining activities and management of potential risks after decommissioning and abandonment. Future activities such as geothermal and subsurface storage are instrumental for realising climate and renewable energy policy goals.

In the Netherlands a mature regulatory framework for the management of risks and supervision of mining activities is in force. This framework is supported by technical assessments and knowledge, including a broad portfolio of hazard and risk tools and instruments. However, there is no centralized administration for the maintenance, quality assurance and dissemination of these tools. Neither is there an established link with the various research agendas on mining effects for the coordination of the development of new tool functionalities. In this context it should also be noted that the allocation of responsibilities and liabilities often differs before and after abandonment of subsurface activities, which is also reflected in the tools being used (e.g. monitoring and managing groundwater contaminations by regional/local authorities).

Considering the expected new and diversifying use of the Dutch subsurface the State Supervision of Mines and the ministry of Economic Affairs and Climate have identified a need for the development of a so-called national risk toolbox and a strategic research agenda to assure the availability and employability of high-quality tools and knowledge to all stakeholders. In their view, the national risk toolbox is a platform to systematically store, maintain and disseminate knowledge and tools (e.g. models, monitoring networks etc), gained through mining experience and specific research programs.

This report presents an inventory of existing tools and put them in context of the mining activities, identifying those areas that are well established or have either limited or lacking tools. This analysis shows the necessity for developing additional knowledge and tool functionalities, and results in recommendations for a national strategic agenda and governance framework for risk tool development and research of mining risks. The study has been commissioned through the Knowledge Program on Effects of Mining (KEM), topic KEM-3a: “Mining effect hazard and risk assessment models Toolbox: ownership, development, public access and quality assurance”

Research and tool development agenda:
A comprehensive technical inventory of mining activities, mining risks and available risk assessment capacities in the Netherlands, are compiled in a proposed research agenda that has been ranked according technical criteria and the expert judgment of the project team. The following research and tool development priorities are proposed:

- Continuation of the Groningen seismicity risk assessment program with focus on the development and deployment of risk model trains (interfacing of additional tool components) and further uncertainty reduction in the seismicity risk assessment.

- Development of risk tools and fundamental knowledge in support of a national risk protocol for geothermal production. Emphasis is put on the expansion of the seismic monitoring and data validation network as well as the implementation of knowledge gained from Groningen.

- Establishment of a knowledge base and validated tools for managing long-term risks of subsidence and leakage related to either (re-)use or abandonment of salt caverns.

- Development of a risk map and tools for the assessment of impacts resulting from rising (mine) ground water including surface uplift and inundation in southern Limburg, and the evaluation of mitigation plans.

- Investigation of the actual risks related to (methane) leakage in abandoned and legacy oil and gas wells. Assess the need for risk tools and protocols to prevent and manage the long-term impacts.

The following generic recommendations are given with respect to the definition and maintenance of this agenda:

- The priorities for the strategic agendas are to be based on a comprehensive technical inventory like the one presented in this report. The technical ranking of priorities should be based on clear and objective criteria and the expert judgment of research institutes and other technical stakeholders involved.

- In addition to technical criteria, the ranking of research agenda priorities should incorporation also additional, non-technical criteria. Examples are societal perception, psychological impacts, economic impacts, etc. It is recommended to query, communicate and approve these criteria based on the input of a wider stakeholder group.

- Implementation of a communication structure and maintenance scheme which allows for both regular strategic agenda updates as well as the adoption of ad-hoc risk issues.

Risk toolbox:
This study has investigated the requirements and specifications of a national risk toolbox aiming to support development, maintenance, dissemination and user-assistance of (certified) tools used to assess and manage risks resulting from mining activities in the Netherlands. It is recommended to:

- Set-up a platform for the administration, maintenance, dissemination and support of risk tools related to mining effects

- Establish a clear connection between the toolbox and related mining effect research programs (e.g. KEM, DeepNL, NCG). The risk toolbox is pivotal to deploying research results through verified risk tools.

- Use the TNO Groningen seismic risk model train and the included individual tool components as a prototype for the development of the risk toolbox platform. Gradually incorporate additional tools from other knowledge institutes (e.g. Deltares and KNMI).

- Facilitate access to tools and protocols through clear communication, documentation and guidelines in co-creation with key stakeholders (end-users and developers).

- Establish a quality assurance framework which is fit-for-purpose and proportional to the complexity and impact of the risk tools. It is recommended to ensure conformance to international QA standards reported in the Aqua Book and associated guidelines. Ensure validation, review and formal embedding of extensions that are needed for mining activities.

- Allocate a long-term annual budget for operating and maintaining the toolbox (including updates, help desk, deploying the online platform). A procedure to request a contingency budget should be available for the development and implementation of new tools when circumstances change, or insights emerge which raise the risk profile.

Governance
The development, maintenance and deployment of risk tools involves a complex set of different tasks and responsibilities which involve interactions between policy makers, regulators, science institutes, tool developers, and end-users such as consultants and advisors. Furthermore, the risk toolbox will be closely linked to national research programs (both in defining new research topics and embedding the outcomes). A governance framework essentially identifies responsibilities and accountabilities with regards to the definition of the strategic agenda on mining effects research and the implementation of the national toolbox for mining risk tools. Typically, governance concerns the following three main aspects 1) defining roles and responsibilities to get things done, 2) identifying ownership, accountability and decision rights, and 3) establishing a clear structure for communication, interaction

and transparency between all parties involved. These aspects are covered in the following recommendations:

- It is recommended to establish a lead consortium of the key national subsurface institutes (TNO, KNMI, Deltares)[1] who are responsible for the technical evaluation and ranking of research topics related to assessment of mining hazards and risks in the Netherlands. The same consortium should be responsible for the development of the national risk toolbox, the maintenance of risk tools and coordination of the quality assurance procedures.

- The national government and supervision (i.e. the Ministry of Economic Affairs and Climate Policy; the State Supervision of Mines) are accountable for both the strategic research agendas and the risk toolbox. This means that they will approve the research and development agendas and decide on funding.

  Communication and interaction structures should be established and agreed upon by the above responsible and accountable parties. The KEM panel and other stakeholders (e.g. representatives from other major institutes such as RIVM, KWR and various universities, end-users, principal developers) should be consulted to review and support the approval of the strategic research and tool development agendas as well as for reviewing the research and tool development outcomes.

[1] TNO, Deltares and KNMI have a long track record with regards to the assessment of mining risks, the development and application of risk tools and the maintenance of national subsurface models and data repositories.

Contents

1 Introduction

This report presents the main findings and recommendations for the KEM Risk Toolbox study. The study was commissioned by SodM (State Supervision of Mines) in 2018, as part of the KEM knowledge program[2], topic KEM-3a "*Mining effect hazard and risk assessment models Toolbox: ownership, development, public access and quality assurance*"[3]. The preliminary results have been presented to the KEM expert panel on July 2nd and November 28th.

1.1 Rationale

Mining activities in the Netherlands remain vital for the supply of energy and to a lesser extend for industrial resources. The main mining activities in the Netherlands, from the present and the past, have been: coal mining, rock salt mining, gas production and storage, oil production, and geothermal energy production. Although gas production - being a dominant mining activity over the past 60 years - steadily declines[4,5], there is an expected increase of new and diversifying activities in the Netherlands such as energy production using geothermal sources.

Exploration, production, deployment and abandonment of mining activities may be associated with effects, such as induced seismicity, surface deformation, leakage and facility hazards. Over the past years, risks and impacts from mining activities have resulted in an accelerated increase of societal concerns and anxiety fuelling political debates in the Netherlands.

But risks are not only related to the period of active deployment (e.g. production, storage). Cases such as coal mining in Limburg and salt mining in Twente show that risks can still develop long after the activity has ceased. Over the past decades thousands of deep wells have been drilled and hundreds of salt caverns have been leached. The abandonment of these locations strongly determines the risk from long-term effects (e.g. 500 year forecast on well corrosion and safety)

An adequate management of risks and the reduction of impacts is therefore key to ensure a safe and publicly accepted deployment and development of mining activities and management of potential risks after decommissioning and abandonment. Specifically, future activities such as geothermal and subsurface storage are instrumental for realising climate and renewable energy policy goals.

In the Netherlands a mature regulatory framework for the management of risks and supervision of mining activities is in force. This framework is supported by technical assessments and knowledge, including a broad portfolio of hazard and risk tools

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[2] The Dutch Minister of Economic Affairs has initiated a public Knowledge Program on Effects of Mining. This knowledge program, called KEM, addresses the recommendations of the Dutch Research Council for Safety (OVV) and aims at enhancing the understanding of hazard and risk of mining activities in The Netherlands.

[3] https://www.kemprogramma.nl/blog/view/57979344/kem-03a-mining-effect-hazard-and-risk-assessment-models-toolbox-ownership-development-public-access-and-quality-assurance

[4] MEA (Ministry of Economic Affairs and Climate Policy), 2018. Natural resources and Geothermal energy in The Netherlands 2017

[5] Van Geuns, L., Juez-Larré, J. & De Jong, S., 2017. Van exporteur naar importeur. De verander(en)de rol van aardgas in Nederland

and instruments. However, there is no centralized administration for the maintenance, quality assurance and dissemination of these tools. Neither is there an established link with the various research agendas on mining effects for the coordination of the development of new tool functionalities. In this context it should also be noted that the allocation of responsibilities and liabilities often differs before and after abandonment of subsurface activities, which is also reflected in the tools being used (e.g. monitoring and managing groundwater contaminations by regional/local authorities).

Considering the expected new and diversifying use of the Dutch subsurface the State Supervision of Mines (SodM) and the ministry of Economic Affairs and Climate Policy (MEA) have identified a need for the development of a so-called national risk toolbox and a strategic research agenda to assure the availability and employability of high-quality tools and knowledge to all stakeholders. In their view, the national risk toolbox is a platform to systematically store, maintain and disseminate knowledge and tools (e.g. models, monitoring networks etc), gained through mining experience and specific research programs.

This report presents an inventory of existing tools and put them in context of the mining activities, identifying those areas that are well established or have either limited or lacking tools. This analysis shows the necessity for developing additional knowledge and tool functionalities, and results in recommendations for a national strategic agenda and governance framework for risk tool development and research of mining risks.

1.2 Goal, objectives and scope

The Knowledge Program on Effects of Mining (KEM) officially started in 2017. The KEM expert panel, the National Research Council for Safety (OVV), and the Team of Directors of SodM concluded that:

- there is a need for a risk toolbox for mining effects
- knowledge gained through the KEM program should be systematically stored and maintained
- such maintenance should be carried out by the Dutch national knowledge institutes (TNO, Deltares and KNMI)

During a workshop on March 12th, SodM, KEM, MEA and TNO explored the functionalities and employability of a validated toolbox capable of assessing and calculating mining risks (probability of effects, hazards and impacts). The outcomes are used to define this study, and to establish the envisioned toolbox and knowledge maintenance.

The recommendations are based on the following results as defined in the study assignment:

- A general overview of the state of play of mining activities and their associated risks and effects (i.e. induced seismicity, subsidence, leakage and damage to environment and infrastructure).

- An inventory of tools and tool components that are commonly used to assess mining effects, impacts and risks in the Netherlands. The tool scope includes induced seismicity, surface deformation, leakage and associated damage (including external safety). The inventory should also include a limited listing of tools used abroad, that could become relevant for the Netherlands in the coming 5 years

- An overview of existing mining risk knowledge and tools and reported gaps in knowledge and tool functionalities. The overview should refer to current knowledge agendas under the KEM, DeepNL and NCG research programs and other reports that have recently listed research needs for evaluating and managing mining risks.

- A definition of urgency and priority for further development and validation of mining risk tools

- A proposal for the development and implementation of a risk-tool management framework (risk toolbox or risk-tool platform) which focuses on tool development, validation, quality assurance, maintenance and dissemination. The proposal should be compliant with common international standards and practices for risk toolboxes.

The study is limited to a generic overview of hazards and impacts. Location-specific and situational risk evaluations and are not included in the scope. Likewise, the identified research questions are not linked to specific cases, except for the Groningen seismicity and the Limburg coal mining cases.

The guidance by KEM expert panel recommends the risk toolbox to focus on models and tools that are:

- available owned, financed and used by public authorities (independence from operators interests)
- covered by rigorous (international) scientific and quality control (scientifically sound, authoritive)
- open and accessible for universities and consultants (open to be used, challenged and improved)
- available at low costs, given 100% publicly finance and easy access

The recommendations in this report provide a basis for the development and of the risk toolbox, and the implementation of a strategic agenda and governance structure. Detailed specifications and a concrete action plan are to be elaborated in a follow-up assignment.

1.3 Report structure

The document is divided into the following chapters:

Chapter 2: Background and definitions of the hazards, risks and impacts covered in this study. Overview of appraised references for the evaluation of research topics.

Chapter 3: An inventory of current state of play with regards to mining activities and their effects and impacts.

Chapter 4: An inventory and evaluation of existing tools relevant for risk assessment of mining activities.

Chapter 5: An overview of requirements for systematic future risk tool maintenance

Chapter 6: An overview of quality assurance models proposed for risk tool development and validation.

Chapter 7: Strategic agenda: A synthesis of current risk tool development priorities and related research agendas.

Chapter 8: Recommendations on establishing a governance framework for mining effects research and risk tool development.

2 Definitions and background

This chapter briefly describes the definitions and background used for this study. It includes a description of main hazard/risk categories and associated impacts, an introduction to the types of tools used for risk assessment and an overview of key references and research programs focusing on hazard and risk aspects.

2.1 Hazards, impacts, risks

2.1.1 Definitions and Risk Bow Tie

In the context of this study, **risk** is defined as the probability or threat of damage, injury, liability, loss, or any other negative **impact** that is caused by **effects** resulting from mining activities[6]. Impacts may be avoided or reduced through preemptive action, either by preventing the causes to occur or by mitigating the consequences of effects.

The hazards discussed in this report are subdivided into four main categories: seismicity, surface deformation, leakage and migration, and facility hazards. Table 2-1 provides a schematic overview of the main hazard categories and underlying mechanisms. Table 2-2 lists the various types of impacts that may result from these hazards. The next sections provide a brief description.

Hazard category	Mechanism	Typical example
Seismicity	Induced earthquakes Triggered earthquakes Generated tremors Natural earthquakes	Groningen gas production Basel (CH) geothermal Fracking (US) Peelrand fault
Surface deformation	Subsidence – reservoir compaction Subsidence – salt cavern convergence Sink holes, collapse, suffusion and sagging Liquefaction	Wadden Sea and Groningen gas production Barradeel salt mining Twente-Rijn (old salt caverns) ‘t Loon (abandoned coal mine) Sendai Earthquake 2011, observed during numerous earthquakes world wide
Leakage and migration	Leakage along well Natural path migration Permeation Restoring groundwater levels	Amtsvenn (DE) gasoil storage Natural gas chimneys North Sea Possibly closed salt caverns Zuid Limburg coal production
Facility hazards	Explosion Blow-out Spills / pollution Emission	Piper Alpha platform (UK) Well Sleen-01 (gas exploration) Tubbergen water injection (transport) Escape of gases

Table 2-1: Overview of main hazard categories, underlying mechanisms and typical examples

[6] As defined by the Dutch Mining Act and Mining Regulations

Impact category	Seismicity	Surface deformation	Leakage	Facility hazard
Damage to houses, built environment, monuments	X	X	X	X
Damage to critical infrastructure, e.g. dykes and levees	X	X		
Pollution of groundwater, surface water, natural environment, ecology		X	X	X
Change of groundwater level, desiccation or wetting		X		
Reduction of air quality, affection of climate			X	X
Personal injuries (physical), casualties	X	X	X	X
Psychological issues	X	X	X	X
Interference (conflict of interests)		X	X	

Table 2-2: Overview of possible impacts related to the various hazard classes. The extent or (future) chance of these impacts depends on the type of activity and preventive / mitigating measures in place. Some impacts have already occurred in the Netherlands

The risks and tools are generally regarded within the context of the Risk Bow Tie framework (Figure ##). At the centre of the bow tie is the risk event itself (e.g. an induced earthquake). The relevant events are characterized and ordered in Table 2-1. On the left side are the hazards that may lead to the risk event (e.g. possible concentration of earthquakes due to differential compaction) as well as the barriers to prevent them from occurring (e.g. adapting production profiles to reduce differential pressure depletion). On the right side are the potential consequences (e.g. damage to buildings) and the controls to mitigate the effects from the risk event (e.g. reinforcing vulnerable buildings and infrastructure).

The risk tools may act on any of the elements in the bow tie, e.g.:

- Tools to investigate the nature, cause and magnitude of the hazard
- Tools to evaluate the effect of various preventive measures
- Tools to calculate the actual risk
- Tools to determine the nature, extent and severity of impact and consequences
- Tools to evaluate how mitigating controls may reduce the impacts and consequences

All in all, the Risk Bow Tie approach itself is considered as a tool, as it provides a structured approach to assess risks, hazards and impacts that are related to a specific mining activity and to design and evaluate preventive measures and mitigating controls.

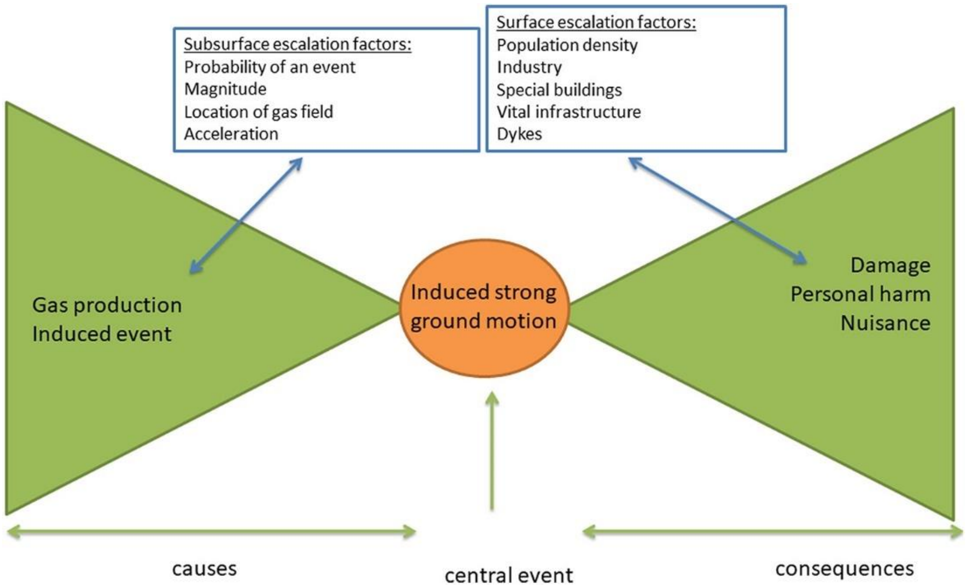

Figure 2-1:Bow-tie with induced strong ground motion as exemplary central event. On the left-hand side, the cause of human induced seismicity is indicated and on the right-hand side the consequences. The escalation factors subsurface and surface play a role on escalating the cause toward the central event and the consequences respectively[7]

2.1.2 *Induced seismicity:*

(Micro-)earthquakes resulting from artificially generated movements along faults or creation of fractures in solid rock. The main mechanisms responsible for noticeable earthquakes capable of causing damage are:

- Increase in stress at existing faults as a reservoir becomes depleted or pressurized and rock (de-)compaction varies at both sides of a fault.
- Increases in stress at existing faults due to continuing pressure depletion or thermal changes.
- decrease of friction in a critically stressed fault due to invasion of fluids during injection or drilling.

Gas reservoir depletion and differential compaction is currently the most common cause for induced earth quakes in the Netherlands. Swarms of small earthquakes have also been detected in the region where mine water rises in Southern Limburg. Recent observations point towards salt caverns and geothermal energy productions as potential sources. Micro-seismic earthquakes may also be generated by fracturing of rock (e.g. caused by high pressure injection of fluids), migration of fluids or vibrations from various activities (e.g. seismic survey acquisition). These events are only detected by sensitive monitoring equipment and rarely noticed by humans. Damage or other major impacts are very unlikely and difficult to correlate with these micro-seismic events.

[7] Thienen-Visser, K., Roholl, J.A., Muntendam-Bos, B.M., 2018. Categorizing seismic risk for the onshore gas fields in the Netherlands. Engineering Geology vol. 237, p. 198-207. https://doi.org/10.1016/j.enggeo.2018.02.004

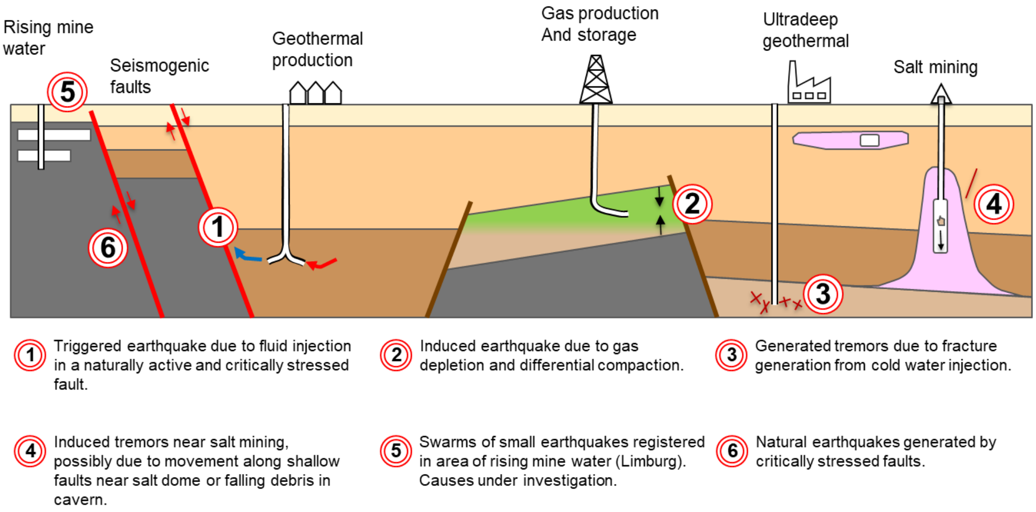

Figure 2-2: Overview of possible artificial and natural causes for seismicity in the Netherlands. The figure is highly schematized and does not represent the subsurface and activities at realistic scales.

2.1.3 *Induced surface deformation*

Gradual or abrupt deformation of the Earth's surface, caused by induced changes in deeper rock formations. Known mechanisms in the Netherlands are:

- gradual subsidence caused by rock compaction (reservoir depletion) or convergence of cavernous spaces (rock salt).
- gradual uplift caused by rock decompaction (reservoir pressurization) and expansion of cavernous spaces (rising mine water).
- abrupt subsidence and formation of sink holes due to roof collapse of cavernous spaces.
- sudden destabilization of, for example, dykes due to liquefaction.

Deformation by landslides is common in many countries with steep surface morphology (mountains) but not in the Netherlands.

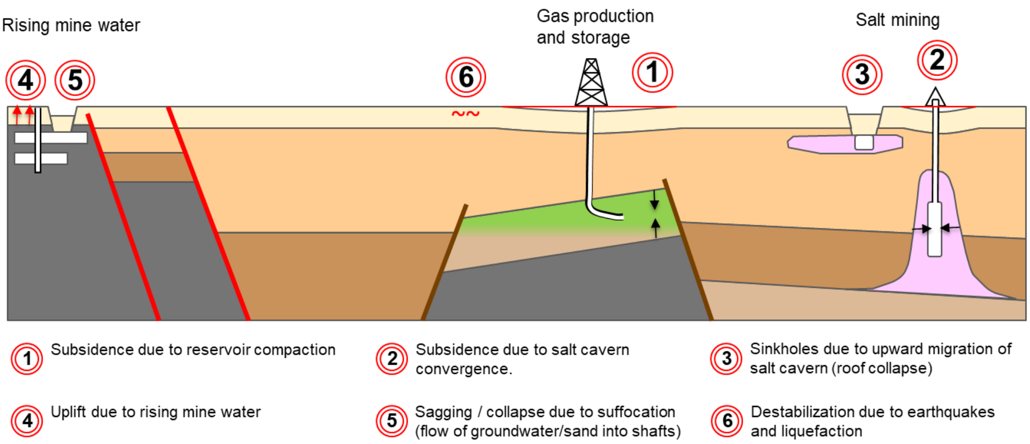

Figure 2-3: Overview of possible causes of surface deformation induced related to mining activities in the Netherlands. The figure is highly schematized and does not represent the subsurface and activities at realistic scales.

Induced surface deformation can also be caused by drainage, largely affecting the near surface deposits. In addition, large parts of the Netherlands are part of the North Sea Basin which subsidence is driven by tectonic forces. Although induced surface deformation caused by mining can be distinguished from tectonic and near surface causes, they need to be considered before concluding that surface deformation is single handed caused by mining. Subsidence risks resulting from shallow/near-surface processes are not included in the scope this study, yet the relation to subsidence induced by mining activities is often essential in the general assessment.

2.1.4 Subsurface leakage and migration

All mining activity as described will disturb the substrata to reach the intended resources, using predominantly boreholes. During exploration, production and even after abandonment, these boreholes (and excavations spaces) will affect the penetrated Formations. Any failure of the integrity of boreholes could have a profound effect on the pristine aquifers that have been penetrated.

In addition, e.g. gas reservoirs, relict salt caverns, and aquifers are used for storage (temporally and permanent) for several applications, including gas buffer, gasoil storage and the discharge of production water. The trend is that the subsurface will be used for even more applications involving storage and injection. The integrity of the storage space is crucial to prevent loss of stored material and more importantly any contamination of the surrounding formation.

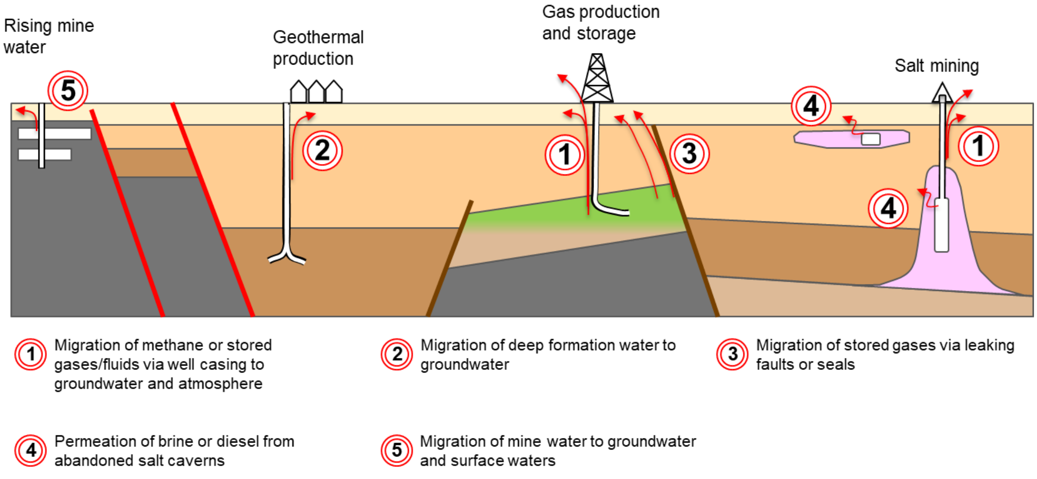

Figure 2-4: Overview of possible causes and mechanisms of leakage and migration related to mining activities in the Netherlands. The figure is highly schematized and does not represent the subsurface and activities at realistic scales.

Leakage and subsequent migration of the produced resources and stored materials will negatively affect the immediate surrounding and if not dealt with properly could have a prolonged effect on a much large area.

Known incidents are related to:

- The leakage of production water into groundwater through damaged boreholes

- Leakage of stored gasoil from relict salt cavern into the surrounding Formations
- Flooding of abandoned mine workings in Limburg, resulting in flooding, subsurface deformation and groundwater contamination.

2.1.5 *Facility hazards*

Exploration and exploitation of subsurface resources and storage capacities are treated like other industrial activities. They are inclined to conduct comparable impact assessments and to implement risk mitigation and prevention measures (e.g. HSE) with regards to their surface activities and surface infrastructure. In general, this category covers a very broad range of aspects (sound, traffic, view, safety, etc.). This study only covers the risks that are directly related to the subsurface activity (e.g. drilling and the extraction, processing, transport and/or injection of gases and fluids). The following potential hazards and risks are considered:

- Spilling of drilling fluids or produced fluids (e.g. formation water) which are captured, treated and stored at the surface. In general, this type of risk is adequately managed with on-site measures which prevent spills to reach groundwater of surface waters as well as various remediation measures.
- Blow-outs and explosions may occur when an unexpected high-pressure gas pockets is encountered during drilling. This risk is generally very small due to the extensive investigations before drilling and the installation of blow-out preventers.
- Emission of toxic gases or green-house gases from the wellbore or storage tanks
- Spilling of fluids from damaged transport pipelines. Normally these leakages can be detected at an early stage

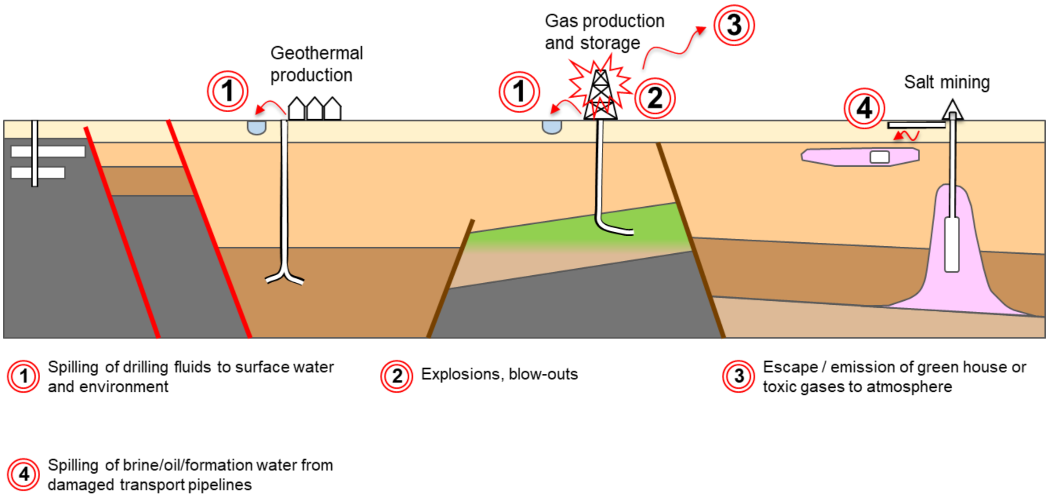

Figure 2-5: Overview of possible facility hazards related to mining activities in the Netherlands. The figure is highly schematized and does not represent the subsurface and activities at realistic scales.

2.2 Research questions on mining effects and risks

The strategic agenda presented in this report is supported by an evaluation of research questions and recommendations, that have been raised in various recent publications, studies and programs. These questions are compiled and categorized in a single excel database and aggregated into common research directions related to the main hazard classes and mining activities. These are discussed in the state of play presented in Chapter 3.

Table 2-3 indicates what is the general focus of the research questions raised in each of the references. Figure 2-6 provides a more detailed scope definition of all the research questions and recommendations that have been incorporated in the database. For the latter it is important to note that the distribution of topics is strongly biased by the focus on Groningen seismicity. The following sections present a brief background for the references that have been included in the inventory.

Reference	Oil & gas	Geo-thermal	Storage	Salt mining	Coal mining
KEM-2018 strategic framework and research agenda	SDLF	SL	SL	DL	D
DeepNL 2018 research program	SD	(S)	SD		
NCG-2018 research topics	S				
SodM-2017 Staat van de sector geothermie		SLF			
EBN-2018 Masterplan Geothermie		SLF			
TNO-2017 H2020 Project IMAGE		S			
DOE-2017 Accelerating breakthrough innovation in CCUS			SLF		
CATO-2014 Linking the Chain			SLF		
De Gemeynt-2018 Routekaart CCS			SLF		
EBN/GasUnie-2018 Transport en opslag van CO2 in NL			SLF		
TNO-2018 Verkenning ondergrondse opslag in NL			SDLF		
Deltares-2012 Risk assess. gasoil storage Marssteden			L		
SodM-2018 Staat van de sector zout				DL	
NAM-2016 Groningen Production Plan	S				
SodM-2014 Na-ijlende gevolgen steenkoolwinning					SDL
TNO-2018 Methaanemissie gerelateerd aan olie/gassector NL	L				
Deltares, Alberta Groundwater flow and gas migration	L				
Deltares-2016 Liquefaction sensitivity shallow subsurface Groningen	SD				
SodM-2018 jaarplan	SD				

Werkprogramma's TNO/Deltares/KNMI	SDL	S	X	X	
EZ-2015 PlanMER structuurvisie schaliegas	SLF				
I&W/EZK-2018: Structuurvisie ondergrond	X	X	X	X	X

Table 2-3: Overview of recent studies which have been evaluated for hazard and risk research topics. Legend: S = seismicity, D = surface deformation, L = leakage, F = facility hazard, X = general

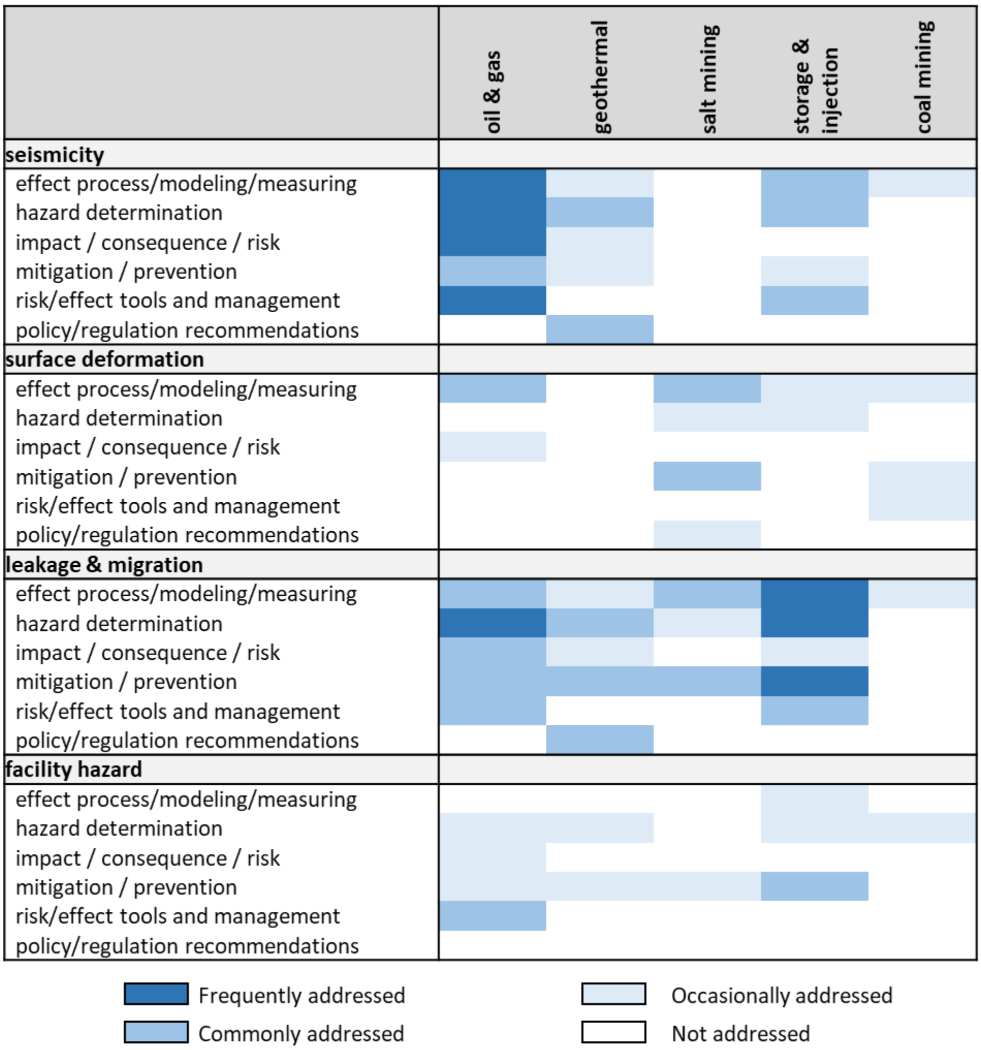

Figure 2-6: Overview of hazard and risk aspects mentioned in the documents listed in Table 2-3. Note that the distribution is strongly biased by the focus on Groningen seismicity

2.2.1 *KEM*

The Dutch Minister of Economic Affairs has initiated a public Knowledge Program on the Effects of Mining. This knowledge program, called KEM, addresses the recommendations of the Dutch Research Council for Safety (OVV) and aims at enhancing the understanding of hazard and risk of mining activities in The Netherlands.

The objectives of the KEM are to:

- accelerate and increase the necessary knowledge development concerning the possible effects and risks of mining activities,
- intensify the multidisciplinary collaboration necessary between national and international research centers and universities,
- develop independent, publicly available, validated and authoritative knowledge and tools for the assessment of mining effect and risks.

The current research projects and proposals in the KEM program predominantly focus on induced seismicity related to gas production and, to a lesser degree, geothermal, storage and salt mining. Subsidence, leakage and facility integrity are sparsely represented. The KEM strategic framework and research agenda published in 2018, provides a more detailed breakdown of research questions. The KEM program addresses the hazard mechanisms as well as the impacts and the tools to evaluate the risks.

The outcomes of this study are intended to be used as a guidance to define the future KEM agenda. The tools developed through the KEM research agenda should ultimately become part the risk toolbox platform.

2.2.2 DeepNL

The aim of the research program DeepNL is to improve the fundamental understanding of the dynamics of the deep subsurface under the influence of human interventions. With DeepNL, the Dutch Research Council (NWO) is giving a concrete response to the advice of the Dutch Safety Board (OvV): ensure that there is a structural and long-term research program into the gas-extraction related problems in Groningen.

The current research projects in DeepNL are all related to investigating the hazard mechanisms. Impacts are not included in the scope.

2.2.3 NCG

The National Coordinator Groningen (NCG) is a cooperation of six municipalities in the earthquake area of Groningen, the Province of Groningen and the national government. The NCG coordinates the actions to make houses, other buildings and infrastructure resistant to earthquake damage. To this end, NCG proposes additional research topics to the KEM program, all of which are focused on the determination of damage resulting from induced seismicity.

2.2.4 Groningen Production Plan (NAM, 2016)

The 2016 update of the Groningen Production Plan includes an inventory of studies and data acquisition activities undertaken and planned to support the assessment of hazard and risk resulting from induced seismicity in Groningen for the next 3-5 years. The main objectives of the Study and Data Acquisition Plan are to:

- Understand the impact of the earthquake hazard on buildings and other structures and the subsequent impact on safety of the community;
- Perform a fully integrated Hazard and Risk Assessment for the Groningen region, with all uncertainties fully and consistently recognized and quantified;
- Identify, evaluate and develop mitigation options to reduce safety risk:
    - Production measures, i.e. changes in the production from the field

- An optimized Structural Safety Upgrading program to identify buildings and/or building elements that pose a safety risk and to establish optimal structural upgrading methodologies
- Measures for industry and infrastructure.

2.2.5 *Geothermal studies*

Specific research agenda topics for hazards and risks related to geothermal production are derived from:

- Staat van de Sector Geothermie (SodM, 2017)
- Masterplan Geothermie (EBN, 2018)
- H2020 Project IMAGE (TNO, 2017)

The “Staat van de Sector Geothermie” provides an overview of risk and hazard issues related to geothermal production in the Netherland and has been derived from observations and interventions by SodM (State Supervision of Mines).

The report “Masterplan Geothermie” mostly looks at the challenges to grow and mature geothermal production in the Netherlands. With regards to safety and hazards it emphasizes the need for fact-finding, hazard/risk knowledge bases, and criteria, protocols and assessment frameworks to ensure a safe and responsible development of the sector.

IMAGE provides a further in-depth view on exploration of ultra-deep and super critical geothermal systems in Europe. Several case studies in the project focus on thermo-mechanical and seismicity-related aspects.

2.2.6 *Subsurface Storage studies*

Specific research agenda topics for hazards and risks related to subsurface storage are derived from:

CCS:

- Accelerating breakthrough innovation in CCUS (DOE, 2017)
- Linking the Chain (CATO, 2014)
- Routekaart CCS (De Gemeynt, 2018)
- Transport en opslag van CO2 in Nederland (EBN-GasUnie, 2018)

Subsurface Energy storage, other:

- Verkenning ondergrondse opslag in Nederland (TNO, 2018)
- Gasoil storage in salt (TNO-Deltares)

The various CCS publications provide an overview of recent risk studies performed as well as remaining technical and regulatory issues to be addressed. Key aspects are potential leakage of CO2 and monitoring

The report “Verkenning ondergrondse opslag in Nederland” lists various research questions that especially relate to storage and buffering of hydrogen in salt caverns and gas fields (behavior, containment, facility integrity).

2.2.7 *Staat van de sector zout (SodM, 2018)*

The report “Staat van de Sector Geothermie” provides an overview of risk and hazard issues related to rock salt production in the Netherland and has been derived from observations and interventions by SodM (State Supervision of Mines). Managing long term effects and risks is a key aspect in the document.

2.2.8 *Methane leakage (TNO, 2018)*

This report presents the results of a reconnaissance of methane emissions in the Netherlands that are related to the oil and gas sector (exploration, production, transport, processing, distribution and storage). It also includes a comparison with other countries across the globe. Recommendations focus on gathering more knowledge regarding leakage at abandoned wells, establishing further standard to monitor leakage and developing measures to minimize risk of leakage at future abandoned wells.

2.2.9 *Long-term consequences of coal mining and salt mining*

SodM, 2014 and GS-ZL, 2016 published Two reports named “Na-ijlende gevolgen steenkoolwinning”, provide an overview of effects and impacts related to rising groundwater in the former Limburg coal mining district. The documents list various effects that have occurred and presents recommendations to better understand and manage future risks (damage to buildings, ground water pollution and quality). While delayed effects are occurring, the GS-ZL 2016 report concludes that there are no direct safety risks because the effects are not resulting in hazards and/or adequate prevention and mitigation measures are in place.

The outcomes of the 2016 GS-ZL study are further elaborated in a recently published report proposing development of an early-warning-system for local differential surface movements, among others based on InSAR data and direct links to other measurement techniques including (photo) inspections and observations.

Kroon, I. and Scheffers, B. 2003. Risk analysis for salt cavern abandonment

This report presents the results of a generic and qualitative risk analysis that has been performed to identify the risks involved in salt cavern abandonment. The tool used in the risk analysis is the ‘Features, Elements and Processes’ methodology. The FEP-method aims to generate a set of relevant risk scenarios based on a comprehensive set of FEP’s in a systematic and transparent way, based on expert judgement. Thus, extremely unlikely and/or rather insignificant FEP’s are not a priori excluded from the analysis.

2.2.10 *Other sources:*

Various other sources which have been evaluated are:

- Recent yearly work programs of TNO, Deltares and KNMI (commissioned by MEA, SodM, MIW)
- Various groundwater studies (Deltares)
- Various policy documents including national strategic environmental assessments for shale gas and structural planning of subsurface activities

3 State of play: Mining activities and risks

3.1 Introduction

This chapter presents and discusses for existing and potential future mining activities in the Netherlands the known hazard events and impacts, expected evolution of impacts, key knowledge gaps and adequacy of tools and risk management protocols (Table 3-1).

Mining activity	Key assets	Status
Oil and gas production	Groningen gas field Small gas fields Oil fields Shale gas and oil	Decline (stop by 2030) Decline Decline Undeveloped, moratorium
Geothermal production	Standard doublets Ultra-deep, enhanced	Upscaling Under investigation
Storage and injection	CO_2 (CCUS) Formation water Natural gas Hydrogen Industrial gases (N_2/He) Gasoil Aquifer thermal energy Radioactive waste	Under investigation Active Active Under investigation Active (N_2) Active Pilot Under investigation
Salt mining	Shallow bedded (Twente) Pillars (Zuidwending, Heilligerlee) Deep (Barradeel, Harlingen)	Active Active Active
Coal mining	Southern Limburg	Ceased, delayed effects

Table 3-1: Overview of existing and future

The known and potential mining effects and hazards are grouped into four categories which are briefly introduced in the following sections. Paragraphs 3.3 to 3.7 present the state of play for each type of mining activity.

3.2 State of play heat maps

The state of play for each mining activity and its related hazards are visualized in so-called circular heat maps. Each heat map ranks four aspects which are briefly explained in the following four sections.

3.2.1 Risk level

The risk level assesses whether the given mining activity and associated type of hazards/effects pose a threat. The following four classes have been defined:

- High: Significant impacts are already occurring or may become likely without further risk interventions (e.g. prevention, mitigation)
- Moderate: Minor to severe yet localized impacts are registered. Future hazard events are either considered to generate minor impacts or the development of the mining activity is still provisional

- Low: Noteworthy impacts are unknown to exist, and the future occurrence of such impacts is considered unlikely
- Not applicable: The risk or hazard is not relevant (at least in the Netherlands and under the current setting)

3.2.2 Need for knowledge

The need for knowledge particularly applies to the understanding of geological processes and the effects of human activities on subsurface behaviour. This also includes the propagation of mining effects towards impacts and the availability of data to assess these effects, hazards and impacts. The following four classes have been defined:

- High: Existing knowledge gaps and lack of data hamper the adequate assessment of hazards and impacts likely to occur
- Moderate: Existing knowledge and data are enough for a general understanding of hazards and risks. Yet there is a need for deeper understanding of certain processes or more data to reduce uncertainties and provide a more accurate determination of the risk.
- Low: There is (very) limited demand knowledge and information for the assessment of current and future risks and hazards
- Not applicable: There is enough knowledge and information for the assessment of current and future risks and hazards (at least in the Netherlands and under the current setting)

3.2.3 Need for tools

The need for tools applies to models, monitoring and measurement equipment, and workflows that are used to register and assess risks and hazards. The following four classes have been defined:

- High: Development of new tools and components is needed to for a complete evaluation of hazards and impacts likely to occur (risk level moderate to high)
- Moderate: Existing tools and components can (need to) be adapted or combined for the evaluation of hazards and impacts in this category.
- Low: The assessment of current and future risks and hazards is supported by a comprehensive and mature set of risk tools.
- Not applicable: There is no need for tools (at least in the Netherlands and under the current setting)

3.2.4 Need for protocols

The need for protocols applies to standards, risk norms, procedures, guidelines, directives, etc. that are defined by an authorized regulatory body for the management of risks and prevention of impacts. The following four classes have been defined:

- High: there is a lack of clear protocols for the management of hazards and impacts likely to occur.
- Moderate: Existing protocols, tools and components need to be adapted or combined for the evaluation of hazards and impacts in this category. Alternatively, protocols used by other mining activities can be adapted for the assessment of hazards and impacts in this category.
- Low: Current and future risks and hazards are adequately managed by a comprehensive and mature set of risk protocols and guidelines.
- Not applicable: There is no need for protocols (at least in the Netherlands and under the current setting)

3.3 Oil and gas production

3.3.1 Seismicity

The heat map in Figure 3-1 summarizes the state of play regarding seismic hazard development and assessment for oil and gas production in the Netherlands.

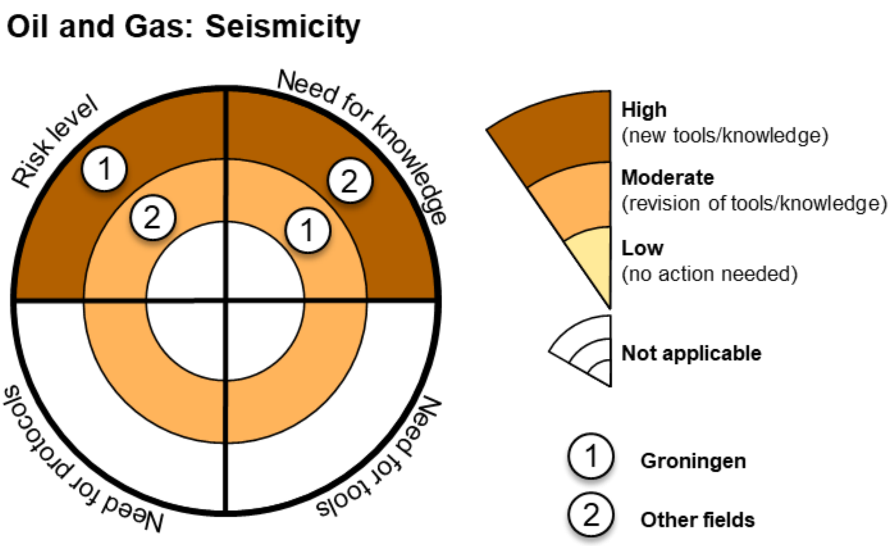

Figure 3-1: Circular heat map describing the status and assessment requirements for seismic hazards in oil and gas production

<u>Risk level: Moderate - High</u>

Gas production in the Netherlands is associated with the occurrence of seismic events. The first seismic event was recorded in 1986 in Assen. Since then more than 1500, mainly small events (M ≤ 3.6) occurred associated with gas production. Most of these are related to the Groningen gas field, which is the largest onshore gas field in Europe. Seismicity in Groningen caused societal unrest and lead to a governmental decision in 2018 to stop gas production before 2030[8]. In addition, a reinforcement program for buildings started (mitigation). Seismic events have also occurred in smaller gas fields both onshore as well as offshore.

For Groningen detailed monitoring and modelling was carried out, resulting in a state-of-the-art hazard and risk assessment[9]. Seismic risk is estimated to be higher than the national safety norm (of 10^{-5} casualties /per year). Hence, the seismic risk level for Groningen is considered high.

Other (smaller) gas fields are generally characterized by a lower seismic activity rate. For these fields a hazard and risk assessment like for Groningen is currently unavailable. Onshore gas production is in decline while no new exploration licenses

[8] Wiebes, E., 2018. Ontwerp-instemmingsbesluit Groningen gasveld 2018-2019.
[9] Van Geuns, L and Thienen-Visser, K (eds), 2017. Induced Seismicity in the Groningen Gas Field, the Netherlands, Volume 96 - Special Issue 5 - December 2017

will be issued. The seismic risk level for the onshore and offshore new and existing gas fields is therefore considered to be moderate.

To date no significant earthquakes have been reported that are related to oil production in the Netherlands. The rest of this assessment therefore focuses on gas production.

Seismic risks are also regarded in the context of hydraulic stimulation (hydraulic fracking) where injected fluids may enter (capable) faults and thereby trigger earthquakes. This was particularly considered as a hazard for shale gas development. Currently there is a moratorium in place which prohibits exploration and production of shale gas and shale oil. Hydraulic stimulation of conventional reservoirs is still practiced, yet these activities have not led to development of seismic risks.

<u>Need for knowledge: High - Moderate</u>
For Groningen, the need for knowledge is moderate. There has been an extensive investment in several applied and fundamental research programs as well as research made available by industry. As a result, the existing knowledge and available data have improved significantly over the past years. Research is still needed and ongoing to improve our understanding of processes in the subsurface of Groningen, yet there are no indications that new research programmes are required in addition to the existing ones.

For the small gas fields there is a lack of knowledge and data to apply in probabilistic hazard and risk models/ It is likely that limited data and knowledge results in overestimations of hazard and risk levels, however this remains unconfirmed. Important knowledge gaps include questions are:

- what is a suitable ground motion model for hazard and risk calculations for the smaller fields?
- what data do we need for such a model?
- what is the fragility of buildings outside of Groningen?
- what is the effect of the shallow subsurface in the rest of the Netherlands?
- Understanding dissolution effects related to large-scale formation water injection in Twente gas fields (Zechstein formations)

The following main topics are under investigation through the KEM knowledge program and other research programs (e.g. DeepNL, NCG):

- fault behaviour,
- influence of fault characteristics on seismic hazard,
- more detailed/extensive fault models,
- effect of reservoir depletion on seismicity,
- seismic hazards from faults above Zechstein level.
- seismic wave propagation to surface movement,
- influence of shallow subsurface on PGA,
- seismic wave propagation through rock salt,
- influence of water bodies on ground movement
- propagation of surface movements to building and infrastructure.
- possibility of seismic impacts on groundwater and salt formations

<u>Need for tools: Moderate</u>
The investigation of seismic hazard and risk from gas production is generally well covered by mature tools and models. The areas with high seismic risk such as Groningen are covered by a dense network of seismometers and accelerometers (KNMI). Composite model trains for the Groningen gas field have been developed in the past by NAM and are currently being developed by TNO (with the intention to incorporate and interface tools from other institutes including KNMI and Deltares), each capable of integrally assessing hazard and impact (building damage and risk) for various production schemes.

The model trains require continuous updates as new knowledge is being incorporated and quality is improved. The TNO Groningen model train is currently being prepared for dissemination and public use. Adaptations of the Groningen tools are required to deploy the model train for small gas fields. The first need is to collect data and knowledge of the small fields before deploying these models for the smaller fields.

Besides the direct seismic responses to production, there is a need for models predicting delayed seismicity in Groningen during phasing-out and eventual ceased production

<u>Need for protocols: Moderate</u>
Mature seismic risk protocols are in place for gas fields in general (both Groningen as well as the small gas fields). Operators are obliged to perform hazard and risk assessments as part of their production plans. The existing protocols will be updated as new information becomes available.

SodM has developed elaborate protocols for hydraulic stimulation which address the use of chemicals, the distance to (capable) faults, integrity of the sealing layers, injection pressures, etc.

3.3.2 Surface deformation

The heat map in Figure 3-2 summarizes the state of play regarding surface deformation hazard development and assessment for oil and gas production in the Netherlands.

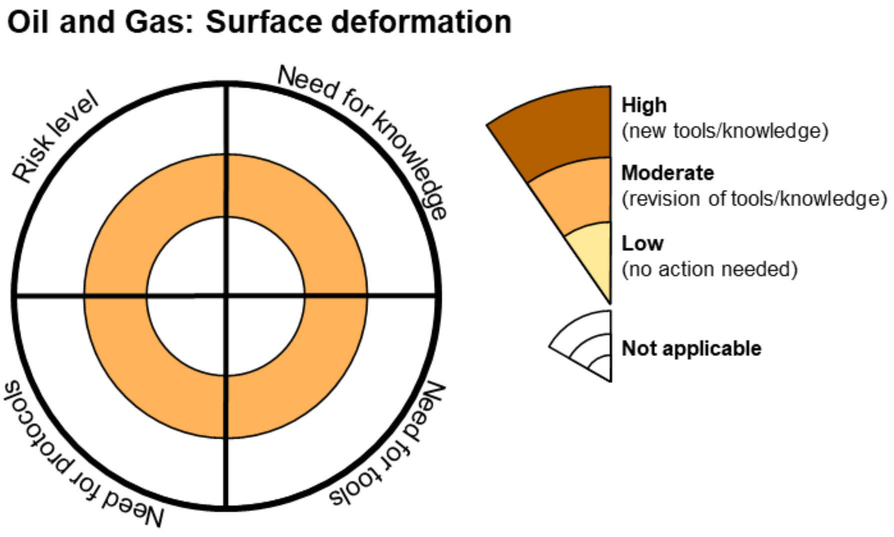

Figure 3-2: Circular heat map describing the status and assessment requirements for surface deformation hazards in oil and gas production

<u>Risk level: Moderate</u>

With ongoing gas production, the pressure in the gas reservoir drops. This leads to reservoir compaction and gradual subsidence at the surface. Resulting subsidence bowls generally exhibit a gentle tilt, which by itself is unlikely to affect houses or infrastructure. Depending on local conditions however, subsidence may affect groundwater and surface water levels which need to be mitigated by water management. Adaptation of the water management strategies could result in near surface e.g. compaction, creep or peat oxidation and could lead to differential surface deformation which in turn could be capable of generating damage to houses. Subsidence in the low-lying coastal areas (e.g. Friesland) may cause salt water intrusion. Strongest subsidence from gas production is recorded above the centre of the Groningen field (ca. 33 cm in 2013), which is due to the extent of the Groningen field, combined with the reservoir height, pressure depletion and compaction of the reservoir rocks.

The risk level for subsidence related to gas production is expected to decrease over time as onshore production is in decline. Gas fields with long production time spans such as Groningen will however continue to subside, even after abandonment. The exact time limit for the subsidence to stop remains uncertain.

<u>Need for knowledge: Moderate</u>

Subsidence caused by gas production is a well-understood process. Current research questions relate to reduction of uncertainties, the understanding of delayed subsidence (especially post-production), and the extraction of the shallow subsurface subsidence processes from the subsidence data. Also, more advanced measurements like InSAR and GPS are incorporated with the levelling data to increase the knowledge on the subsurface processes that cause subsidence.

<u>Need for risk/hazard tools: Moderate</u>

Reservoir compaction and subsidence tools are generally mature and well embedded in existing hazard and risk protocols. Development of tools is focused on long term processes, the incorporation of more, different, types of data (levelling, GPS, InSAR) and uncertainties.

Need for protocols: Moderate
Adequate protocols are in place for managing subsidence effects from gas production. Subsidence is specified in gas production plans and closely monitored. In vulnerable areas such as the Wadden Sea, traffic light systems are in place (‘Hand aan de Kraan’). Subsidence is managed through production controls. The gradual development of subsidence generally allows for mitigation of impacts through water level management. Additionally, damages cause by subsidence due to gas depletion are paid by the mining company as stated in the Mining Law (art. 24 lid 1q).

3.3.3 *Leakage and migration*

The heat map in Figure 3-3 summarizes the state of play regarding leakage and migration hazard development and assessment for oil and gas production in the Netherlands.

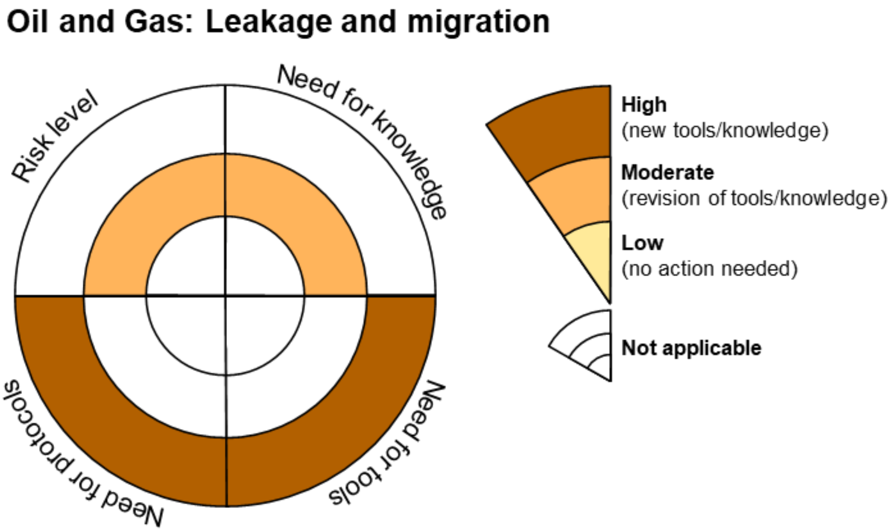

Figure 3-3: Circular heat map describing the status and assessment requirements for leakage and migration hazards in oil and gas production

Risk level: Moderate
At any production- or exploration well there will be a risk for subsurface leakage and migration. Oil, gas, formation water or injection fluids could leak when there is damage to the well. Damage could be caused mechanically or chemically from the inside of the well or the outside. Not only the transported material could be abrasive also the environmental conditions can be hostile corroding and weathering the materials of the wells. Do note that this applies not only to active wells but also to abandoned wells.

In addition, leakage risks are also regarded with hydraulic stimulation (hydraulic fracturing). This relates to chemicals used as well as the pressures applied and the distance of frack propagation

Risks are classified as moderate because not only the degradation of wells is a slow process, also the infiltration processes of the gases and liquids is often limited in quantity. Depending on injection rates and pressure differences, this process may be limited to areas of several tens of meters around the well, especially if the leakage of the well is surrounded by a low permeable aquitard.

A problem is that leakage (and subsequent migration) may go unnoticed for some time. If larger quantities of fluids or gases escape from a well up and are in contact with an aquifer, this could cause damages to larger areas and affect groundwater reserves. Do note that this will result in larger pressure differences or pressure fluctuations causing a decrease in production. Which should trigger the operator to inspect the well integrity.

Leakage of gas may also occur in pipelines for transport (at the surface or buried). The oil or gas will dissolve in the groundwater and because of transport in the groundwater spread and cause large-scale pollution of the groundwater. Pipelines are well monitored, and unforeseen pressure differences will be noticed immediately. If leakage is identified as a cause effective measures can be taken quickly and decisive.

Methane emissions at (abandoned/operating) wells appears to be limited at this moment. However, the abandonment of gas and oil fields will likely increase These abandoned gas and oil fields form an increasing threat for leakage and migration. Although the materials of well will weather over time the risks remain moderate since abandoned wells will most likely have a limited volume of relict fluids or gases that will negatively affect the surrounding environment.

Subsurface and groundwater pollution can damage the environment, and when it migrates to (fresh water) aquifers, it is direct threat for drinking water resources and crops and could cause significant health issues. This may lead to non-mitigatable damage.

<u>Need for knowledge: Moderate</u>
The processes associated with leakage and migration are reasonably well understood. Well integrity is monitored during exploration and production. However, there is a relent concern for the integrity of legacy wells and abandoned wells. Research questions are therefore focused on the assessment and monitoring of subsurface leakage from legacy wells and abandoned wells.

Research question mainly concern the long-term leakage risks from wells. What is the quality of the seal mechanisms on the long term? What is the effect of external microbial corrosion on wells and pipelines? There is a need for monitoring abandoned wells and the analyses of long-term leakage effects of abandoned fields on groundwater quality, including the effects of methane leakage to surface- and groundwater. In addition, more advanced questions regard the investigation of the natural self-healing capability of penetrated shale and salt layers? And the improved understanding of vertical migration pathways (from reservoirs to the surface).

Need for risk/hazard tools: High

Many wells will be abandoned in the near future. Appropriate risk and monitoring tools are necessary to avoid long term (post-abandonment) impacts that could be poorly mitigatable. A monitoring program and tools will help to minimize risks and impact. It is important to establish connection with soil and groundwater research and risk tool boxes that are available.

Need for protocols: High

Existing tools are mainly used on case-by-case basis, often driven by local concerns and are not structurally addressed. Governance and QA are spread over different actors/stakeholders causing diffusive attitudes by all stakeholders. Furthermore, connection with soil and groundwater risk tool boxes has not been formally established. Governance on tool development, composition and implementation needed as potential long-term effects (post-abandonment) may become a national concern.

SodM has developed elaborate protocols for hydraulic stimulation which address the use of chemicals, the distance to (capable) faults, integrity of the sealing layers, injection pressures, etc.

3.3.4 *Facility hazards*

The heat map in Figure 3-4 summarizes the state of play regarding facility hazard development and assessment for oil and gas production in the Netherlands.

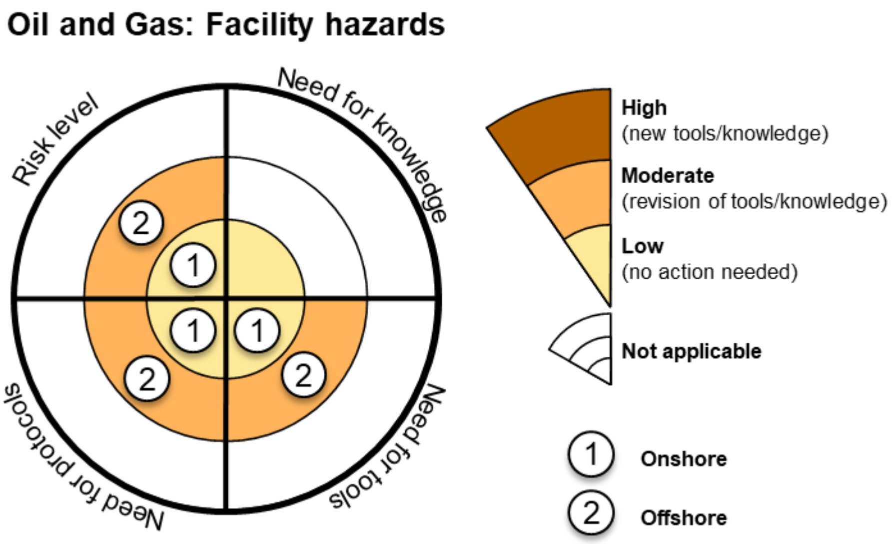

Figure 3-4: Circular heat map describing the status and assessment requirements for facility hazards in oil and gas production

Risk level: Low - Moderate

The risk level for onshore oil and gas production facilities is generally low. Past incidents are known including the blow-out of the well Sleen-2 in 1965, spills and gas releases, and occasional injuries of personnel working on site. Nowadays drilling and production activities are regulated by strict safety protocols. This includes among others the use of blow-out preventers, safety valves and the definition of safety areas surrounding the mining activities. Sites are designed to prevent eventual spills from reaching surface and groundwater resources.

For offshore drilling the situation is quite similar, yet a moderate risk level is assigned since many platforms are starting to age. Corrosion and wear may lead to incidental release of substances that could spill into the seawater. Distal offshore platforms may be difficult to reach when there is a major incident. The further development of this risk depends on the progress of decommissioning and plans for platform re-use.

Need for knowledge: Low
Current research programs focus on developing safe and cost-effective decommissioning strategies and investigation of leakage and pollution hazards of dated offshore platforms.

Need for risk/hazard tools: Low - Moderate
Projects like North Sea Energy (TKI) and NexStep (EBN) focus on planning the options for platform re-use. There is a need for proper decision tools that include risk aspects. The issue of re-use is less relevant for the onshore production sites.

Need for protocols: Low - Moderate
Decommissioning of offshore production and transport infrastructure may require additional hazard and risk protocols.

3.4 Geothermal production

3.4.1 Seismicity

The heat map in Figure 3-5 summarizes the state of play regarding seismic hazard development and assessment for geothermal energy production in the Netherlands.

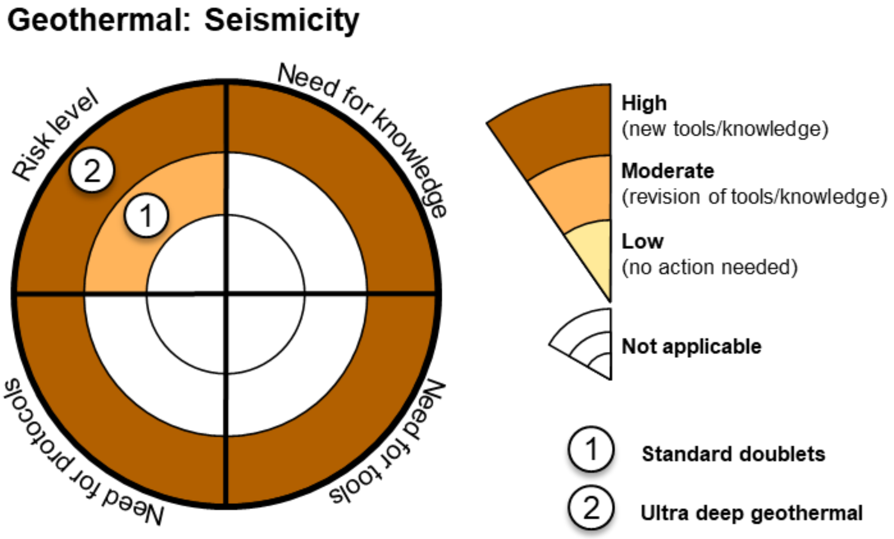

Figure 3-5: Circular heat map describing the status and assessment requirements for seismic hazards in geothermal energy production

Risk level: Moderate - High
Present geothermal systems in the Netherlands are characterized by relatively shallow (1,5 - 3 km depth) operations using doublets (one well for injection and another well for production)[10]. In a doublet system, the pressure should be in equilibrium soon after the start of the geothermal operation. Only stresses due to temperature effects (cooling down) could increase over time.

Close to one geothermal system in the south of the Netherlands a few small (M≤2 2,0 events have taken place. It is unclear, at this moment, whether these events are related to geothermal production operations. This, combined with the relatively small experience with geothermal systems leads to a seismic risk level for geothermal systems in the Netherlands to be moderate. However, new developments include the start of Ultra Deep Geothermal (UDG) pilot projects (2020-2030). These operations are planned at much larger depths (4-8 km). In general, the UDG operations have a larger potential seismic risk and could increase the risk level in future. A higher risk level follows from the assumption that reservoir stimulation will play an important role in UDG operations. Abroad, larger earthquakes have occurred where these Enhanced Geothermal Systems have been placed near seismogenic or stressed faults (e.g. Basel).

Need for knowledge: High
There is a fundamental need for understanding triggers of seismic events in geothermal operations (e.g. effects of injection on naturally stressed faults, fault classifications, protocols for well placement and injection near faults). Water injection in a seismic active area could lead to altered stress states at existing faults due to local temperature and pressure changes. Fault slip may occur due to the changed stress state. Therefore, research on e.g. the effects of injection on stressed faults and fault classification has high priority.

For the UDG operations detailed knowledge of the deeper crustal structure around proposed wells is currently lacking and is required for a proper estimation of seismic hazard and risk.

Future geothermal development will be in areas and depths that are different than the well-known areas and depths for hydrocarbon exploration in the Netherlands. Exploration targets will be more complex, the geological setting will be less-known and overall uncertainty will be higher. To reduce these uncertainties there is need for better geological understanding of these less-known areas in the Netherlands.

The mitigation of seismic risk for geothermal operations and the effectiveness of possible mitigation actions should be further explored.

Need for risk/hazard tools: High
Urgency is mainly related to existing doublets and plans for new doublets in regions with stressed / active faults. Major seismic events leading to damage of buildings and infrastructure could affect geothermal developments in a broader sense and thereby hamper the national ambitions to increase renewable energy production.

[10] MEA (Ministry of Economic Affairs and Climate Policy), 2018. Natural resources and Geothermal energy in The Netherlands 2017

Although experienced seismic events are limited in both magnitude and number, their occurrence is reason to put certain doublets on hold. The development of adequate seismic risk assessment protocols and tools of geothermal projects has high priority. Each geothermal site should be adequately monitored for seismic activity.

Need for protocols: High
First outline of a Seismic Hazard and Risk Assessment protocol is under development. Furthermore, there is a guideline with respect to maximum allowed injection pressure in order not to disrupt the confining layers.
There is no formal framework for development and maintenance of geothermal hazard and risk tools available yet.

3.4.2 *Surface deformation*

The heat map in Figure 3-6 summarizes the state of play regarding surface deformation hazard development and assessment for geothermal energy production in the Netherlands.

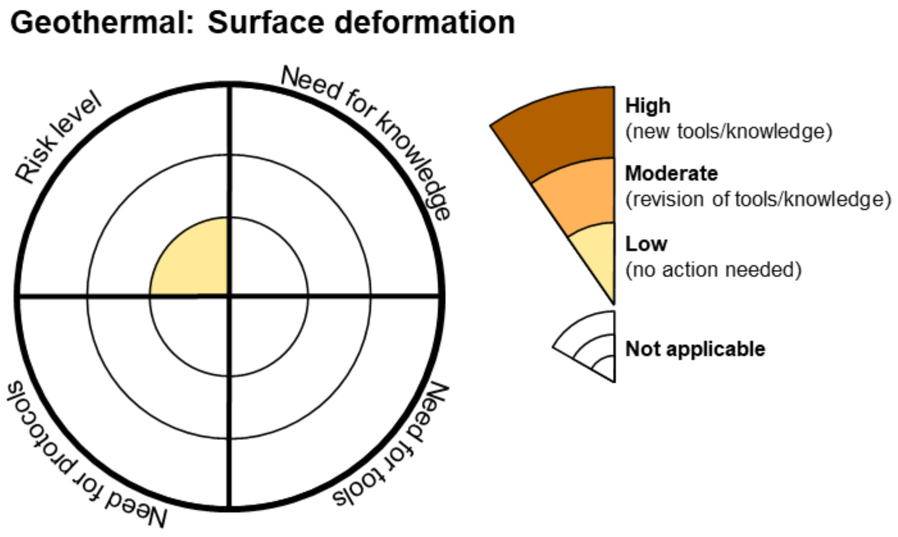

Figure 3-6: Circular heat map describing the status and assessment requirements for surface deformation hazards in geothermal energy production

Risk level: Low
There are, to date, no known risks in the Netherlands that are caused by subsidence due to geothermal energy production. Geothermal systems in the Netherlands consist of (multiple) injection and production wells to maintain the pressure and water mass balance at the reservoir level. Issues are known to exist in other countries where thermal energy is produced without re-injection of the cooled water. This may cause the reservoir to deplete and will therefore generate significant subsidence. As this type of geothermal operations does, and will not, exist in the Netherlands the risk level is deemed low.

Although current protocols prescribe that re-injection should take place in the same, connected aquifer (i.e. to prevent net pressure differences), this may be difficult to achieve in complex reservoir settings (non-permeable faults, interfingering sands, channels, etc.). In these cases, a slight increase or drop of pressure may occur respectively at the injection and production well.

Need for knowledge: Not applicable
Subsidence and uplift are considered irrelevant in geothermal production in the Netherlands. The use of doublets results in zero net injection or production of water and thus no regional increase or decrease of aquifer pressures over time.

Need for risk/hazard tools: Not applicable
Subsidence and uplift are considered irrelevant in geothermal in the Netherlands.

Need for protocols: Not applicable
Subsidence and uplift are considered irrelevant in geothermal in the Netherlands.

3.4.3 Leakage and migration

The heat map in Figure 3-7 summarizes the state of play regarding leakage and migration hazard development and assessment for geothermal energy production in the Netherlands.

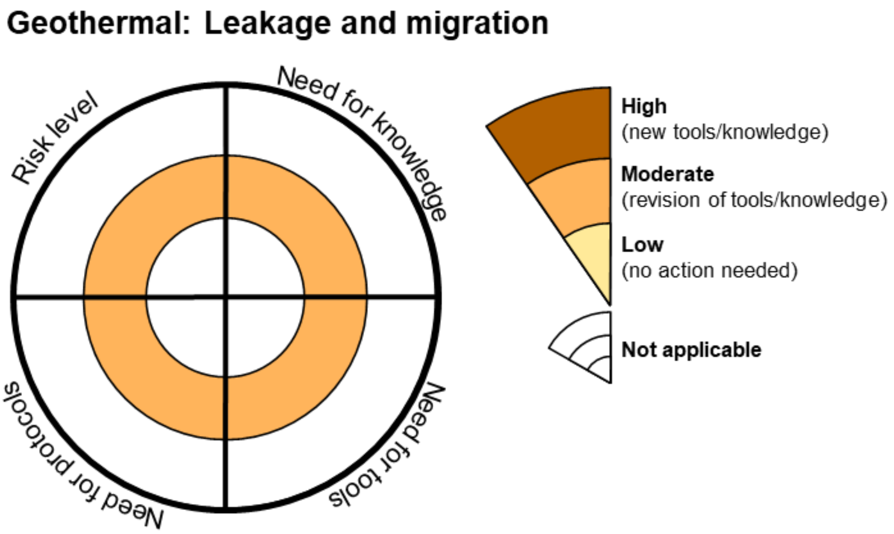

Figure 3-7: Circular heat map describing the status and assessment requirements for leakage and migration hazards in geothermal energy production

Risk level: Moderate
At any production- or exploration well there will be a risk for subsurface leakage and migration. Formation water or injection fluids (brine) could leak when there is damage to the well. Damage could be caused mechanically or chemically from the inside of the well or the outside. Not only the transported material could be abrasive also the environmental conditions can be hostile corroding and weathering the materials of the wells. Do note that this applies not only to active wells but also to abandoned wells. Problems with leakage have occurred in the recent past. Insufficient well design lead to failing of well integrity (Pijnacker/Ammerlaan). Unwanted (co-) production of oil (Pijnacker/Ammerlaan) has been observed, and co-production of dissolved gas is observed in most doublets.

Risks are classified as moderate because not only the degradation of wells is a slow process, also the infiltration processes of the gases and liquids is often limited in quantity. Depending on injection rates and pressure differences, this process may be limited to areas of several tens of meters around the well, especially if the leakage of the well is surrounded by a low permeable aquitard.

A problem is that leakage (and subsequent migration) may go unnoticed for some time. If larger quantities of fluids or gases escape from a well up and are in contact with an aquifer, this could cause damages to larger areas and affect groundwater reserves. Do note that this will result in larger pressure differences or pressure fluctuations causing a decrease in production. Which should trigger the operator to inspect the well integrity.

Subsurface and groundwater pollution can damage the environment, and when it migrates to (fresh water) aquifers, it is direct threat for drinking water resources and crops and could cause significant health issues. This may lead to non-mitigatable damage.

Need for knowledge: Moderate
Concerns for well leakage are comparable to oil & gas production and raise research questions on long-term well integrity and leakage prevention of abandoned wells.

The processes associated with leakage and migration are reasonably well understood. Well integrity is monitored during exploration and production. However, there is a concern for the integrity of legacy wells and abandoned wells. Research questions are therefore focused on the assessment and monitoring of subsurface leakage from legacy wells and abandoned wells.

Research question mainly concern the long-term leakage risks from wells. What is the quality of the seal mechanisms on the long term? What is the effect of external microbial corrosion on wells and pipelines? There is a need for monitoring abandoned wells and the analyses of long-term leakage effects of abandoned fields on groundwater quality, including the effects of methane leakage to surface- and groundwater. In addition, more advanced questions regard the investigation of the natural self-healing capability of penetrated shale and salt layers? And the improved understanding of vertical migration pathways (from reservoirs to the surface).

Need for risk/hazard tools: Moderate
Existing national plans for geothermal production imply that many wells will be drilled in the coming decades. There are tools to assess the potential for a region and design doublets. Does the current telescopic well design for geothermal heat extraction – in combination with lifecycle well integrity monitoring – provide adequate barriers and is overall integrity guaranteed? New tools should include the risk of a leak in the casing, and the presence of strategic ground water resources. The long operational lifetime of wells and potential post-abandonment effects are key aspects to be investigated at an early stage

It has been shown that the coproduction of oil and gas is a real risk? A tool using present knowledge of oil and gas field will help to anticipate on the presence of hydrocarbons.

<u>Need for protocols: Moderate</u>
Existing tools are mainly used on case-by-case basis, often driven by local concerns and are not structurally addressed. Governance and QA are spread over different actors/stakeholders causing diffusive attitudes by all stakeholders. Furthermore, connection with soil and groundwater risk tool boxes has not been formally established. Governance on tool development, composition and implementation needed as potential long-term effects (post-abandonment) may become a national concern.

3.4.4 *Facility hazards*

The heat map in Figure 3-8 summarizes the state of play regarding facility hazard development and assessment for geothermal energy production in the Netherlands.

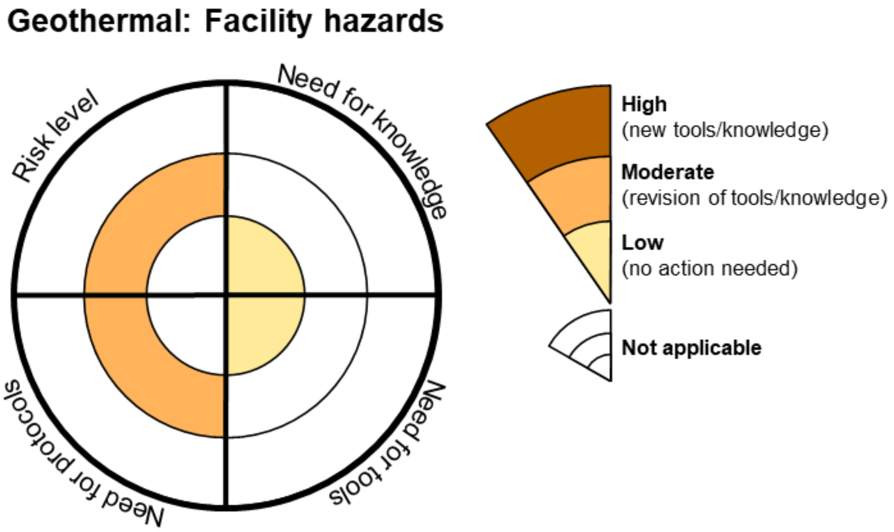

Figure 3-8: Circular heat map describing the status and assessment requirements for facility hazards in geothermal energy production

<u>Risk level: Moderate</u>
The main surface-related risks for geothermal production are:

- Environmental damage and injuries resulting from (uncontrolled) escape of hydrocarbons and hot saline water (blow-outs) during drilling, well-operations and production.
- The mixing and/or contamination of fresh water (surface and subsurface) due to spilling of produced saline water
- Health and safety risks for on-site personnel

The publication “Staat van de Sector Geothermie” (SodM, 2018) reports various concerns regarding the acknowledgement and management of above risks by the geothermal sector in the Netherlands. Even though examples of good practices exist, there is a general sense that environmental risks and safety risks are insufficiently recognized and that regulations are not always properly followed.

SodM concludes that the causes are related to a still weakly developed safety culture (focus on business case), operational inexperience, and insufficient sharing of knowledge. So far, several incidents have been reported with regards to spilling of (saline) water that are produced during formation testing. Several projects have been put on hold by the State Supervision of Mines because regulations and protocols were not properly followed. The risk level for geothermal facility hazards is defined as moderate. There is an established basis for preventing and managing facility risks, yet action is needed to bring this into good practice. Urgency is needed due to the expected growth of the Dutch geothermal sector.

<u>Need for knowledge: Low</u>
There is extensive knowledge available from the mature oil and gas sector. The question is, how to ensure that this knowledge and experience becomes incorporated by the geothermal sector.

<u>Need for risk/hazard tools: Low</u>
Adequate risk tools are already available from the mature oil and gas sector and salt mining sector. Key issues are related to the proper implementation of tools rather than their development.

<u>Need for protocols: Moderate</u>
Over the past decennia, the experiences in the oil and gas sector have evolved in a robust set of practices and protocols for safe operations and adequate risk management. Additional measures are recommended by SodM to ensure that these protocols and practices are properly embedded in geothermal operations.

3.5 Storage and buffering

3.5.1 Seismicity

The heat map in Figure 3-9 summarizes the state of play regarding seismic hazard development and assessment for storage and injection in the Netherlands.

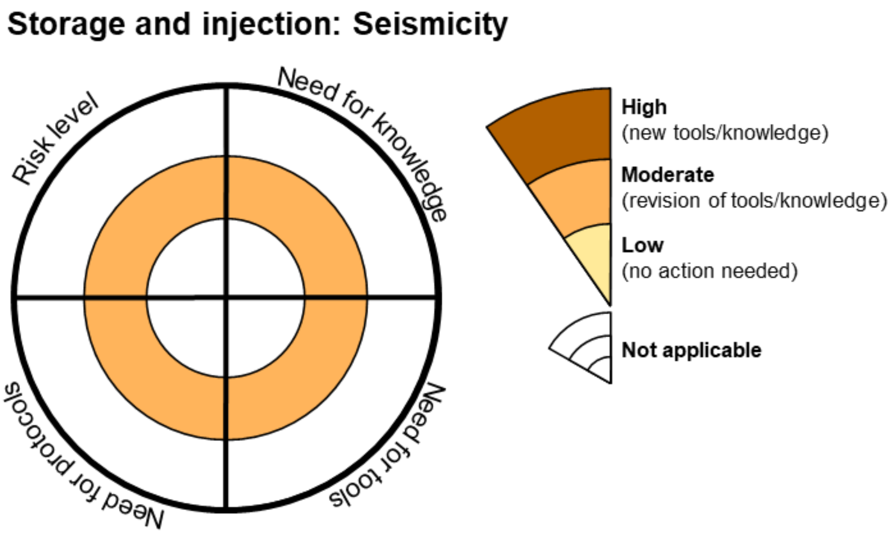

Figure 3-9: Circular heat map describing the status and assessment requirements for seismic hazards in storage and injection

Risk level: Moderate
Injection of fluids and gases into porous formations leads to increasing pressures and possibly a build-up of differential stresses along faults which may be released through induced seismic events. However, geomechanical modelling of storage in a depleted reservoir near Bergermeer, that showed large $3<M<3.5$ events in the production phase, predicted a stabilisation of the subsurface in the storage phase. So far, only minor events ($M<1$) have been recorded at underground gas storage sites in the Netherlands during cushion gas injection and cyclic gas production/injection. There are no known impacts.

In the US, injection of formation water in aquifers has triggered several induced earthquakes of higher magnitudes. The main cause is the increase of pressure above the natural (original) level. Furthermore, injection sometimes takes place in areas that are already characterized by natural seismic activity. Formation water injection in the Netherlands is only allowed in depleted gas fields. Original pressures before gas production started may not be exceeded.

Small earthquakes have been recorded near salt caverns used for storage. It is unclear whether these small events are related to the storage. So far, these earthquakes have not led to damage or other impacts.

Need for knowledge: Moderate
The main knowledge gaps in this regard are related to the seismic response of (cyclic) gas production/injection and waste water injection. Existing gas storages are already in operation since 1996 and have been produced in the years before. Knowledge concerning induced seismic events gained during the production phase, is considered while selecting and developing storages. So far, there haven't been seismic events urging significant efforts in new research programs. A further need for research may be raised in case significant upscaling of storage activities is expected (e.g. increasing capacities at existing sites or developing new sites).

Need for risk/hazard tools: Moderate
The development of new onshore storage sites in depleted gas fields (e.g. hydrogen) is still highly uncertain. In case of new onshore storage development, the need for risk/hazard tools is mainly related to the extension of the seismic monitoring network. Depending on the scale of development, next-gen seismic risk forecasting tools may be needed.

Plans for offshore storage of CO_2 are already in a more advanced stage. The impacts of seismic events here are generally quite small.

Need for protocols: Moderate
Seismic risk protocols exist for the existing onshore storage sites. Revision of these protocols may be required when new storage technologies are developed onshore. Examples include the injection protocols for disposal of formation water in depleted gas fields where the injection pressures are limited to a level that guarantees the integrity of sealing layers.

3.5.2 Surface deformation

The heat map in Figure 3-10 summarizes the state of play regarding surface deformation hazard development and assessment for storage and injection in the Netherlands.

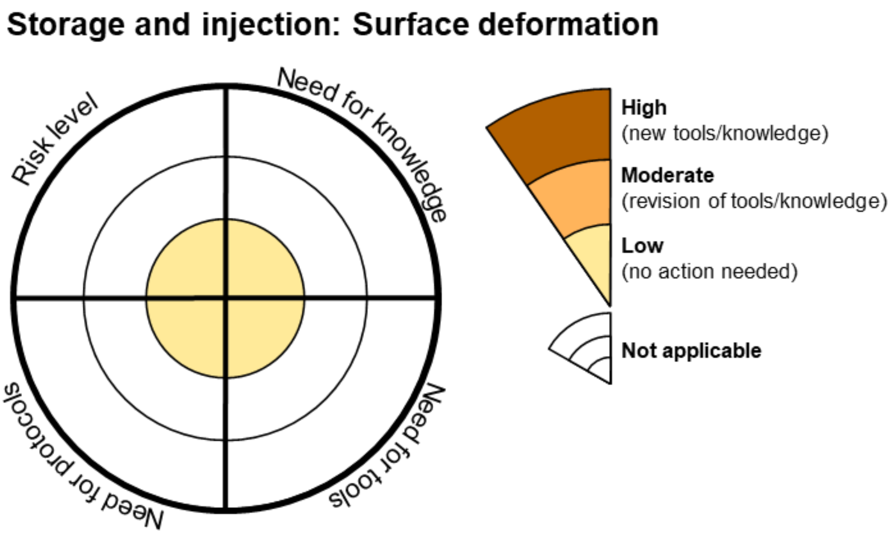

Figure 3-10: Circular heat map describing the status and assessment requirements for surface deformation hazards in storage and injection

<u>Risk level: Low</u>

The average pressure in a gas or oil field after injection is not allowed to exceed the original pressure (i.e. before production). In other formations (e.g. salt caverns[11] and aquifers) the average pressures after injection should stay well below (i.e. max. 80%) the lithostatic pressure. Permanent filling and re-pressurization of a depleted gas field may therefore lead to a (partial) reversal of the compaction that occurred during gas production. As a result, injection and storage will either maintain a certain surface level (e.g. in salt caverns that would otherwise converge and generate subsidence) or partially restore a former surface level (in the case of injection in depleted gas fields). In underground gas buffers (cyclic injection and production) an alternating pattern of subsidence and uplift may be seen in the order of a few cm’s (UGS Norg shows a +/- 1 cm subsidence/uplift every year).

In general, the risks of subsidence and uplift in storage and buffering activities is assumed to be low. Due to the depth of the storage and buffering activities the subsidence/uplift will have a very slight slope. It is unlikely that differential surface deformation occurs due to these activities to a degree that it is enough to generate damage to houses and infrastructure. Eventual consequences to ground water levels can be mitigated with water management (dams, pumping, adjustment of water levels). These mitigation measures could lead to differential surface deformation and, therefore, damage.

Except for the water injection sites, there are currently no onshore permanent storages that would generate a lasting surface deformation effect. Permanent

[11] It is possible that a need for salt cavern storage space will develop. In this case the leaching of storage caverns may cause significant subsidence effects. These are discussed under salt mining.

storage of CO_2 will be deployed in offshore gas fields where uplift and subsidence effect have little or no impact (away from the coastal and Wadden Sea areas).

Need for knowledge: Low
The currently available knowledge is adequate for assessing and managing storage-related surface deformation effects and impacts.

Need for risk/hazard tools: Low
The currently available tools are adequate for assessing and managing storage-related surface deformation effects and impacts.

Need for protocols: Low
Adequate regulation and supervision for managing surface and uplift in current storages and buffers is in place.

3.5.3 Leakage and migration

The heat map in Figure 3-11 summarizes the state of play regarding leakage and migration hazard development and assessment for storage and injection in the Netherlands.

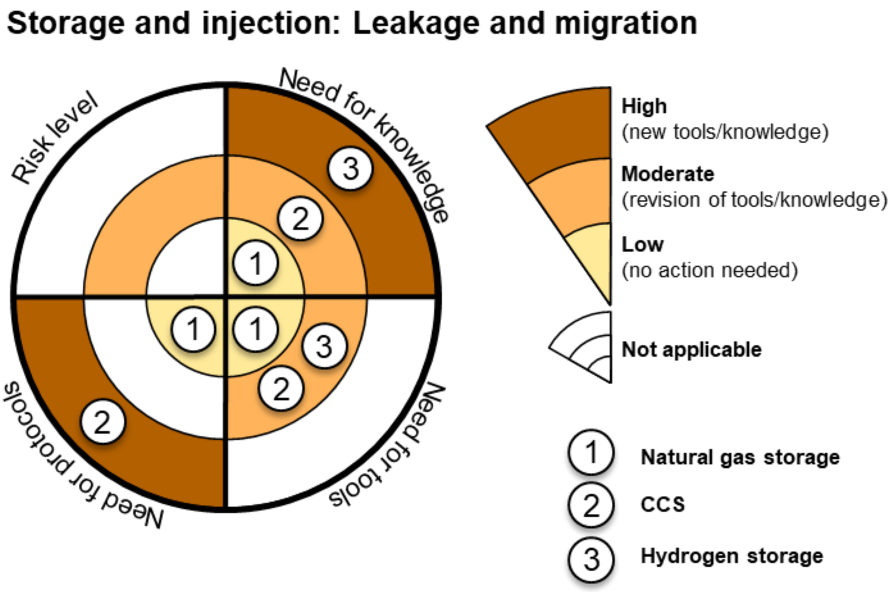

Figure 3-11: Circular heat map describing the status and assessment requirements for leakage and migration hazards in storage and injection

Risk level: Low - Moderate
At any production- or exploration well there will be a risk for subsurface leakage and migration. Formation water, injected or produced fluids or gases could leak when there is damage to the well. Damage could be caused mechanically or chemically from the inside of the well or the outside. Most storage substances are known to affect the wells. e.g. H2 the well steel or CO2 the well cement. This may lead to failing well integrity and leakage. Not only the stored material could be abrasive also the environmental conditions can be hostile corroding and weathering the materials of the wells. Do note that this applies not only to active wells but also to abandoned wells.

Risks are classified as moderate because not only the degradation of wells is a slow process, also the infiltration processes of the gases and liquids is often limited in quantity. Depending on injection rates and pressure differences, this process may be limited to areas of several tens of meters around the well, especially if the leakage of the well is surrounded by a low permeable aquitard.

A problem is that leakage (and subsequent migration) may go unnoticed for some time (Amtsvenn (DE) gasoil storage). If larger quantities of fluids or gases escape from a well up and are in contact with an aquifer, this could cause damages to larger areas and affect groundwater reserves. Do note that this will result in larger pressure differences or pressure fluctuations causing a decrease in production. Which should trigger the operator to inspect the well integrity.

In Germany (close the Dutch border) there has been a major incident in 2014 with gasoil leaking from a damaged single-cased well. This has had a major impact on groundwater and environment (oil spills) in the surrounding region. Severe pollution of groundwater/surface water/soil, including the death of several cows. Ground water remediation programs and instalment of containing walls were amongst used to contain and resolve the pollution. The use of double/multi-cased wells in the Netherlands strongly reduces the risk for this type of incidents.

For storage there are additional risks. Permeation or migration of injected fluids/gases from the reservoir towards groundwater or the surface, could occur if injection pressures exceed the maximum seal strength (failure of reservoir containment). This is mainly prevented by setting safe injection limits (below initial pressures). Leakage/migration can also occur at places where legacy wells penetrate the seal above the storage reservoir. Incomplete information introduces a degree of uncertainty and risk (e.g. CCS). Last but not least, injection may affect the reservoir and seal due to dissolution and chemical corrosion effects. An example is large-scale injection of formation water in gas fields in the Twente region (dissolution of Zechstein carbonates and evaporites).

Leakage/spilling of storage fluids/gases may occur in the pipelines (supply and production). The transported materials can dissolve in the groundwater and because of transport in the groundwater spread and cause large-scale pollution of the groundwater. Pipelines are well monitored, and unforeseen pressure differences will be noticed immediately. If leakage is identified as a cause effective measures can be taken quickly and decisive.

Large unexpected emissions of gases such as CO2 and hydrogen to the atmosphere will affect air quality, possibly leading to health issues or acute dangerous situations.

Subsurface and groundwater pollution can damage the environment, and when it migrates to (fresh water) aquifers, it is direct threat for drinking water resources and crops and could cause significant health issues. This may lead to non-mitigatable damage.

<u>Need for knowledge: Moderate</u>
Key research questions relate to the influence of stored fluids/gases on reservoir. (formation of hazardous substances), seal (deterioration) and well casing/cement

(integrity). Some are of fundamental nature. The need for knowledge varies per storage technology:

- Natural gas storage: Low need for knowledge
- CCS (Carbon Capture and Storage) and heat storage: Moderate need for knowledge
- Hydrogen storage and other materials: High need for knowledge
- Natural gas storage: Low need for knowledge. Using depleted gas reservoirs for the buffering of natural gas is an integral part of the current gas infrastructure. This practise is well defined monitored and has a low need for the development of additional knowledge.
- CCS: Moderate need for knowledge. CCS has been studied in the CATO programs and the current PORTHOS project. Demand for new knowledge is primarily driven by location specific settings and the societal acceptance of such locations.
- Heat storage: Moderate need for knowledge. ATES is widely studied and used in the near subsurface under relative strict conditions such as temperature and volume neutrality over the seasons. High temperature storage sees questions on the effects on (micro) biological activity and lithological/geotechnical properties.
- Hydrogen storage: High need for knowledge development. There is a demand for various topics such as an improved understanding besides the known topics on well integrity. For instance, seal properties, the impact of stored substances on seal such as H2. How will this affect the risk of losing containment? Modelling of leakage pathways, speed, dispersion, reactivity and precipitation, understanding the formation of chimneys, and the influence on groundwater resources at risk. An Improved understanding of hydraulic conductivity along (in)active faults, migration velocity through fractures (various substances). The Influence of injection and stored media on reservoir formations and surrounding rock (physical processes) how will this affect the risk of losing containment.

Possibly the need for knowledge will raise when concrete storage projects are expected to emerge. This knowledge should then extend to the entire subsurface system.

<u>Need for risk/hazard tools: Moderate</u>
Urgency for tools is divided again in low urgency for natural gas storage. For the storage of other materials there is a moderate need for tools. This is driven by the assessment that the tools for natural gas could be adjusted to fit other substances such as CO2 or H2. Although CO2 storage is an integral part of the energy transition plans of the government the actual projects still need to be developed. Also, for other gases such as Hydrogen, storage is under investigation as future option (uncertain trend). If hydrogen storage will be used on a large scale in the future, there will be an urgent need to update the existing risk/hazard tools.

<u>Need for protocols: Low - High</u>
There is a great variety in types of subsurface storage applications and substances. Existing tools are spread over different developing organizations. There is lack of a coherent governance and QA framework. Connection with soil and groundwater risk tool boxes not formally established. Governance on tool development, composition

and implementation needed as potential long-term effects (post-abandonment) may become a national concern.

Water injection protocols are used for example to monitor corrosion, regulate the use of corrosion inhibitors, etc.

3.5.4 Facility hazards

The heat map in Figure 3-12 summarizes the state of play regarding facility hazard development and assessment for storage and injection in the Netherlands.

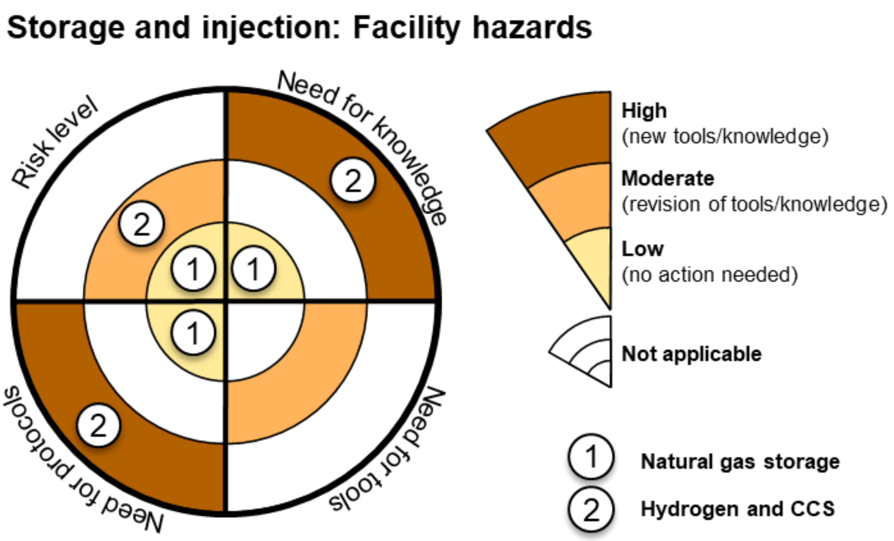

Figure 3-12: Circular heat map describing the status and assessment requirements for facility hazards in storage and injection

Risk level: Low - Moderate
The buffering of natural gas and nitrogen and the storage of formation water is generally covered by adequate risk management procedures and safety protocols. There have been some incidents (spills) with transport of formation water. The facility risk level is therefore considered low.

The risks of possible future storages (mainly CO2 and hydrogen) are still under investigation. As development of such storages is still contingent, the risk level is considered moderate. Concerns are mainly related to

- contamination of ground water and surface water due to spills and leakages in pipelines
- Injuries and affected air quality due to sudden releases and explosions of gases (e.g. hydrogen)
- Increased CO2 emissions from leakages at transport and injection infrastructure

Need for knowledge: Low - High
The effects of hydrogen on transport and storage infrastructure are current focus areas for research. Hydrogen may affect the integrity of steel alloys. Furthermore, hydrogen is known to trigger (bio)chemical reactions in the subsurface which may eventually lead to the formation of toxic substances (e.g. H2S, organic acids).

Although hydrogen production is a mature process in the Netherlands, there is no specific experience with regards to subsurface storage of pure hydrogen.
There is already a quite extensive knowledge base for CO2 storage facility risks in general (various international research projects and programs, test sites, etc.). Current investigations focus on the site assessments and the development of risk management plans for planned CO2 storage projects (e.g. Porthos).

There are currently no critical knowledge gaps with regards to facility risks of underground natural gas storage, hydrogen storage and water injection.

<u>Need for risk/hazard tools: Moderate</u>
Mature tools are available for facility risk assessment of natural gas buffering, nitrogen buffering and formation water storage.

New types of subsurface storage (e.g. CO2, hydrogen) may require adaptation of existing facility risk tools.

<u>Need for protocols: Low - High</u>
The buffering of natural gas and nitrogen and the storage of formation water is generally covered by adequate risk management procedures and safety protocols. For CO2 storage and hydrogen buffering, protocols are still under development however. Current attention focuses on the establishment of injection plans, risk management plans, monitoring plans and abandonment plans that are required for CO2 storage operations.

3.6 Salt solution mining

3.6.1 Seismicity

The heat map in Figure 3-13 summarizes the state of play regarding seismic hazard development and assessment for salt mining in the Netherlands.

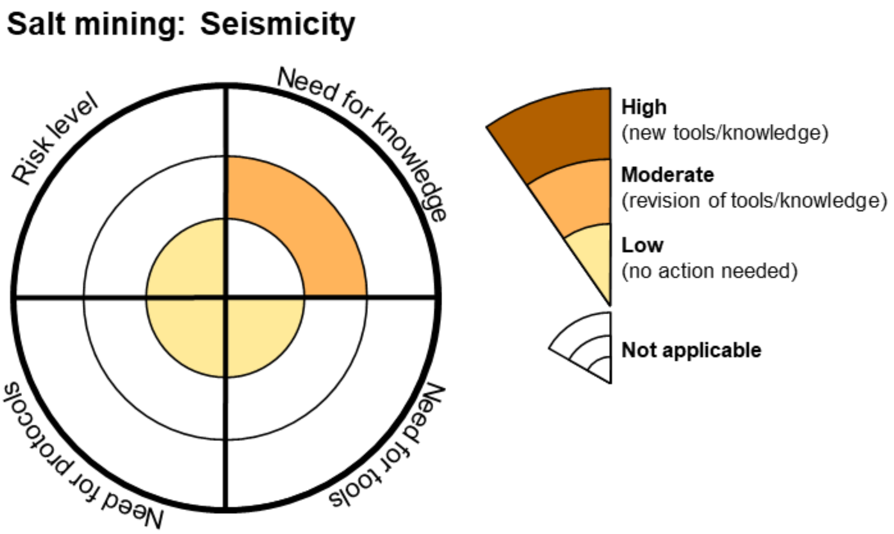

Figure 3-13: Circular heat map describing the status and assessment requirements for seismic hazards in salt mining

Risk level: Low

At the end of 2017 the first small events (M<1.3) were registered in the direct vicinity of a salt dome in production (Heiligerlee) at shallow depth (< 1.5 km). These events could be located due to the improved Groningen monitoring network. Early 2019 another small shallow event was recorded and located near the neighbouring salt dome Zuidwending. These events are small and may be related to stress release along shallow faults near the salt domes or small-scale processes within the domes. Further research has indicated a change in the shape of the cavern. It is possible that a part of the cavern ceiling has fallen into the cavern thus generating a small seismic event[12]. The occurrence of these events is recent and detailed monitoring and modelling is expected to provide more information on hazard and risk, which is currently estimated as low.

Need for knowledge: Moderate

The mechanism of the recent seismicity in the direct vicinity of existing salt domes in production is not clear. Improved detailed monitoring combined with waveform modelling is expected to provide more insight in the processes involved. This information is essential in assessment of related hazard and risk. Convergence of caverns and subsidence could lead to altered stress states near the salt formation, leading to a reactivation of existing faults in the direct vicinity of the salt dome or to a loss of cavern integrity. Another possible cause for shallow seismicity is thought to be related to mechanical effects in the caprock of a salt pillar.

Need for risk/hazard tools: Moderate

Detailed seismic monitoring of salt domes in production contributes to a better knowledge of processes leading to seismicity. In 2018 this was realized around the Heiligerlee salt dome. Tools are available to model seismic waveforms in a heterogeneous subsurface. Extension of seismic monitoring networks near other salt production and gas storage sites is under evaluation.

In addition, risk scenario tools like the “Features, Elements and Processes” methodology (FEP) [13]may help to further asses and understand the chain of mechanisms leading to seismic risks.

Need for protocols: Low

Only few low magnitude seismic events have been observed that appear to be related to salt production and gas storage in salt caverns. These recent observations have led to the discussion whether protocols should be reviewed (especially in face of the upcoming abandonment of salt caverns and potential development of new salt caverns for storage purposes (e.g. H2, compressed air).

3.6.2 Surface deformation

The heat map in Figure 3-14 summarizes the state of play regarding surface deformation hazard development and assessment for salt mining in the Netherlands.

[12] Kamerbrief 11 oktober 2018, verzoek over aardbevingen bij zoutwinning, kenmerk DGETM / 18253698

[13] Kroon, I. and Scheffers, B., 2003. Abandonment of solution mined salt caverns in the Netherlands, part 1 Review, part 2 Best practices and methods. TNO Report

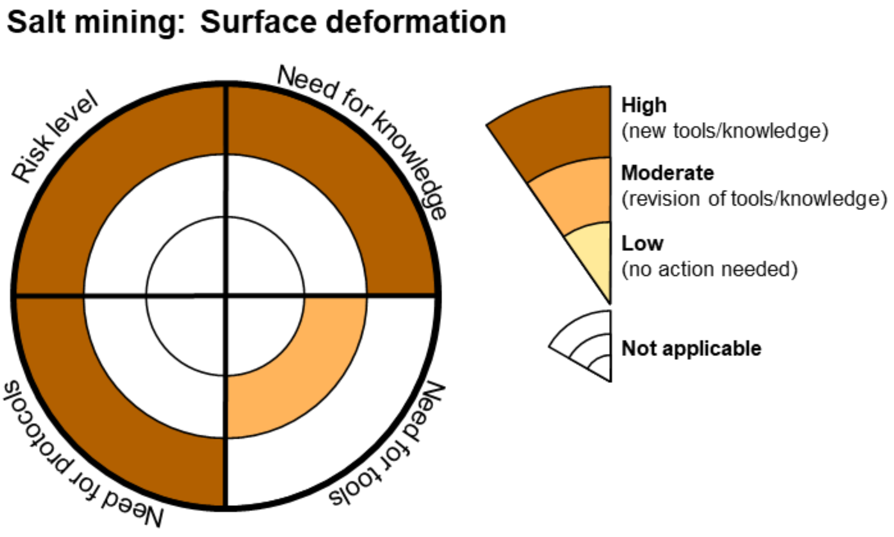

Figure 3-14: Circular heat map describing the status and assessment requirements for surface deformation hazards in salt mining

<u>Risk level: High</u>
Salt is mined in the Netherlands using salt solution mining where water is injected into a salt body which dissolves the salt present. This mixture of brine is produced and converted into salt at the surface. Subsidence is certain to occur (during and after mining) due to squeezing of the salt (lower pressure in cavern than in surrounding strata) and subsequent convergence of the cavern. During a period of several years a subsidence bowl develops of several km's in diameter and maximum several cm's to dm's depth. Subsidence is gradual, both in time and space. The amount of subsidence, rate of subsidence and size of the subsidence bowl depends on the quantity of salt mined and nature of the salt formation (e.g. formation depth which determines the plastic behaviour of rock salt).

Depending on local conditions however, subsidence may affect groundwater and surface water levels which need to be mitigated by water management. The combination with natural processes in the shallow subsurface (e.g. peat oxidation) may lead to differential surface deformation which in turn could be capable of generating damage to houses. Strong subsidence in the low-lying coastal areas (e.g. Friesland) may cause salt water to intrude fresh water resources. The Wadden Sea ecosystem is particularly vulnerable to subsidence as the area is also affected by relative sea level rise.

Sudden subsidence may occur when the salt roof crumbles off and the cavern slowly migrates upwards to a point where the overburden becomes instable and collapses (sink hole). As the salt roof crumbles, the fallen off blocks take more volume, thereby filling the cavern. This may stop the process and prevent a sink hole. Sink holes are very local phenomena directly above the cavern. Some past examples are known for the oldest shallow caverns in Triassic salt layers (Twente-Rijn concession). Salt, nowadays, is mined according to Good Salt Mining Practices, which prevents the development of instable caverns. Risks such as roof collapse, upward migration and development of sinkholes are only associated with some older caverns in the TWR concession. Monitoring of the instable caverns allows enough time to take adequate measures (5-10 years in advance). Collapse of old (poorly designed) caverns could cause damage to buildings and infrastructure directly above the cavern. These effects are very local and unlikely to occur with current salt mining practises and monitoring.

Rate of salt mining has been mostly constant over the past years with a few new concessions being awarded near the existing ones (5). It is expected that salt mining and production will continue at a similar level as today. Possibly there are extensions of current mining concessions. It is expected that the re-use of caverns for storage (e.g. Hydrogen) will increase (notably by 2030). This may have an impact on the way caverns as designed and mined.

<u>Need for knowledge: High</u>
The main research question and concern relates to long term subsidence, especially after abandonment of the salt caverns and prevention/monitoring of the collapse process. There is little data and research available concerning the behaviour of caverns after closure/abandonment. As salt mining may become more important in the future, the need for knowledge on this subject is high.
Otherwise, subsidence during salt production is a well understood and predictable process. Collapse is also well understood and mostly prevented in modern salt mining.

<u>Need for risk/hazard tools: Moderate</u>
Many caverns are to be closed and abandoned. The issue of long-term subsidence is an important topic for all current mining locations. There is also a need for more monitoring to predict and monitor the behaviour of the caverns during salt production and abandonment given the possible increase in salt mining and storage in future.

<u>Need for protocols: High</u>
The main need for protocol revision is linked to the management of long-term subsidence effects after salt production has ceased. This includes practices for safe abandonment, monitoring of post-production subsidence effects and eventually mitigation measures.

Adequate protocols are in place for managing subsidence effects from salt production. Subsidence is specified in salt production plans and closely monitored. In vulnerable areas such as the Wadden Sea, traffic light systems are in place Subsidence is managed through production controls. The gradual development of subsidence generally allows for mitigation of impacts through water level management. Additionally, damages cause by subsidence due to gas depletion are paid by the mining company as stated in the Mining Law (art. 24 lid 1q).

There may be a need to set up a composite model train for the integral and consistent assessment of long-term subsidence (post closure/abandonment).

3.6.3 Leakage and migration

The heat map in Figure 3-15 summarizes the state of play regarding leakage and migration hazard development and assessment for salt mining in the Netherlands.

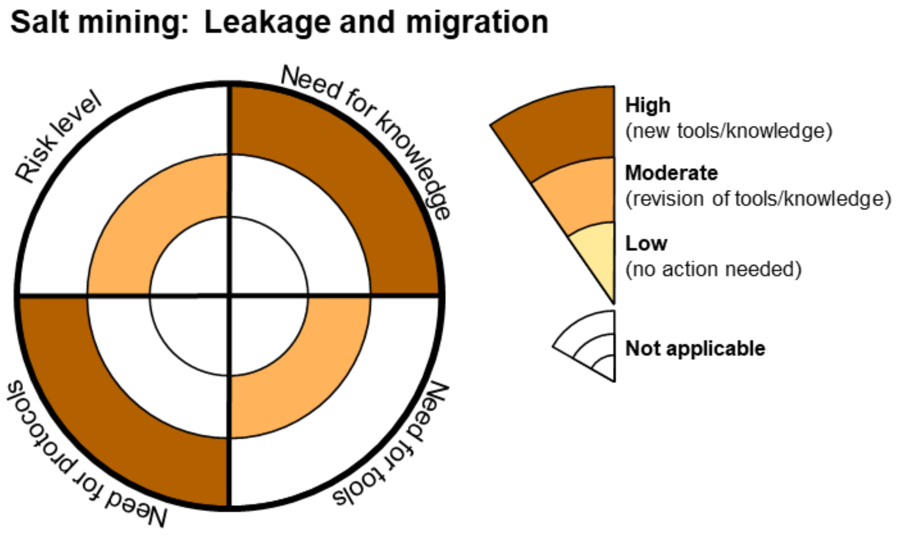

Figure 3-15: Circular heat map describing the status and assessment requirements for leakage and migration hazards in salt mining

<u>Risk level: Moderate</u>

At any production- or exploration well there will be a risk for subsurface leakage and migration. Formation production fluids (brine) could leak when there is damage to the well. Damage could be caused mechanically or chemically from the inside of the well or the outside. Not only the transported material could be abrasive also the environmental conditions can be hostile corroding and weathering the materials of the wells. In Veendam, the caverns have developed as a complex labyrinth. Ca. 40.000 m3 of diesel have remained. Recently a sudden escape of a large volume of brine was noted. The complexity makes this system rather unpredictable. While in Twente, gasoil has leaked from old wells, because of insufficient well connections. The groundwater pollution has been remediated.

Modern wells are developed according to criteria that should minimize the risk of failing integrity.

Risks are classified as moderate because not only the degradation of wells is a slow process, also the infiltration processes of the gases and liquids is often limited in quantity. Depending on injection rates and pressure differences, this process may be limited to areas of several tens of meters around the well, especially if the leakage of the well is surrounded by a low permeable aquitard.

A problem is that leakage (and subsequent migration) may go unnoticed for some time. If larger quantities of fluids or gases escape from a well up and are in contact with an aquifer, this could cause damages to larger areas and affect groundwater reserves. Do note that this will result in larger pressure differences or pressure fluctuations causing a decrease in production. Which should trigger the operator to inspect the well integrity.

In addition to risks on well failure leakage could occur from the caverns to the surrounding formations. Permeation or migration of brine and (non-recoverable) diesel from the cavern. After cavern closure, the pressure increases in the cavern.

Brine and diesel may find a way out via small developing cracks and reach (fresh water) aquifers. With larger escape paths developing, this process may take place suddenly. In case of old (poorly designed) caverns, the upward migration (roof crumbling and collapse) may lead to a release of brine and gasoil around the cavern. In general, deep leakage from wells and caverns may be adequately blocked by the presence of capable sealing formations, thereby preventing the migration towards (fresh water) aquifers and surface waters.

Subsurface and groundwater pollution can damage the environment, and when it migrates to (fresh water) aquifers, it is direct threat for drinking water resources and crops and could cause significant health issues. This may lead to non-mitigatable damage.

<u>Need for knowledge: High</u>
Concerns on well leakage are comparable to oil & gas production and raise research questions on long-term well integrity and leakage prevention of production and abandoned wells. The research questions furthermore relate to the long-term containment of sealing formations. As convergence takes place, pressure increases with possible escape of brine and diesel (permeation, formation of cracks). There is necessity to understand long term permeation effects and solution of salt, migration of brine and diesel. And to improve our knowledge of the process of penetration of brine into surrounding strata and the groundwater system.
Mapping of risks and establishment of risk management/protocols for cavern abandonment.

<u>Need for risk/hazard tools: Moderate</u>
Like with subsidence, the long-term containment of diesel/brine in caverns and migration pathways to groundwater becomes important with the foreseen abandonment. Many caverns are to be closed and abandoned. The issue of long-term subsidence is an important topic for all current mining locations. There is also a need for more monitoring to predict and monitor the behaviour of the caverns during salt production and abandonment given the possible increase in salt mining and storage in future.
There may be a need to set up a composite model train for the integral and consistent assessment of long-term subsidence (post closure/abandonment).

<u>Need for protocols: High</u>
The main need for protocol revision is linked to the management of long-term leakage effects after salt production has ceased. This includes practices for safe abandonment, monitoring of post-production subsidence effects and eventually mitigation protocols.

Connection with soil and groundwater risk tool boxes has not been formally established. Governance on tool development, composition and implementation needed as potential long-term effects (post-abandonment) may become a national concern.

3.6.4 Facility hazards

The heat map in Figure 3-16 summarizes the state of play regarding facility hazard development and assessment for salt mining in the Netherlands.

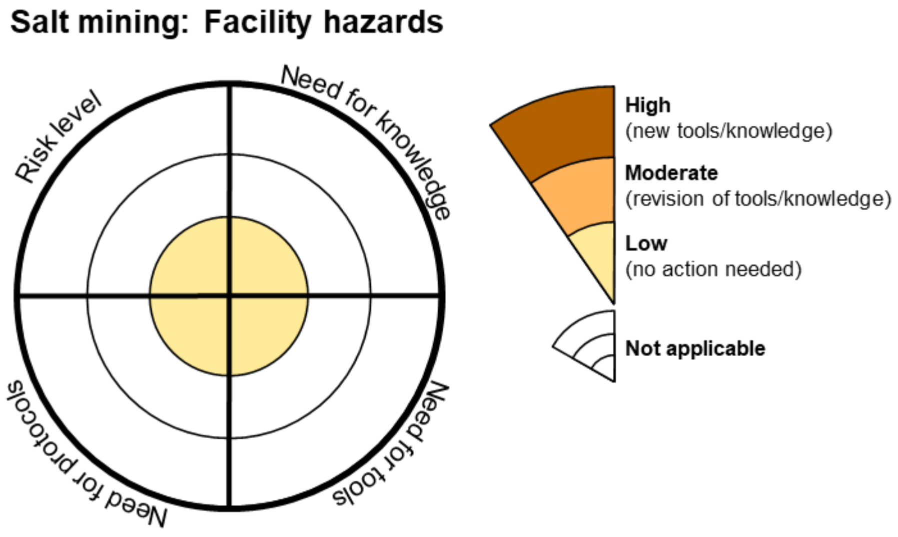

Figure 3-16: Circular heat map describing the status and assessment requirements for facility hazards in salt mining

Risk level: Low
Possible causes for hazards and impacts are related to corrosion of facility infrastructure, pipelines, etc. (caused by brine) that may ultimately lead to failure and release of fluids. There have been several issues in the past with leakage and pollution from transport lines and leakage of a gasoil blanket from a cavern in the Twente-Rijn concession. Other facility hazards typically include site accidents (e.g. damaging of well head production infrastructure, brine blow-out). Safety protocols and monitoring of critical facility elements keep the risk level to low. Eventual surface spills can be remedied by (timely) pumping away polluted water.

Need for knowledge: Low
There are no knowledge gaps that require immediate attention.

Need for risk/hazard tools: Low
There are no urgent issues that would require revision or new development of risk tools for facility hazards.

Need for protocols: Low
Salt mining is a mature process where facility safety and risk management protocols are well embedded in the current operations.

3.7 Coal mining

3.7.1 Seismicity

The heat map in Figure 3-17 summarizes the state of play regarding seismic hazard development and assessment for coal mining in the Netherlands.

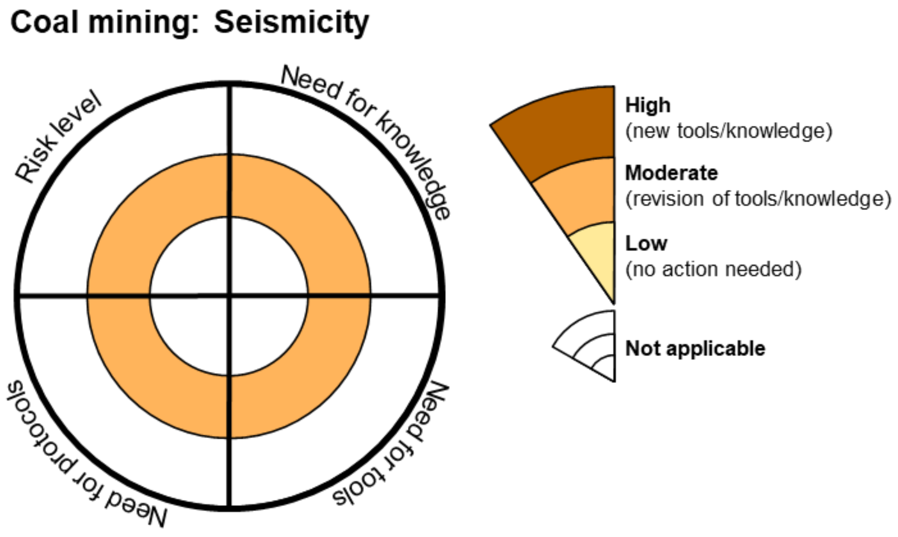

Figure 3-17: Circular heat map describing the status and assessment requirements for seismic hazards in coal mining

<u>Risk level: Moderate</u>

After abandoning of the coal mines in south of the Netherlands 1974, the region experienced the effects of a rise in groundwater level. Swarms of shallow seismicity occurred in the Voerendaal region in the period 1985-1986 and 2000-2002 and in the Heerlen and Landgraaf region in 2018 (11 earthquakes with magnitudes between 0,5 and 2,4 on the Richter scale). These events occur outside the Roer Valley Graben and may be caused by an increase of in water level in the mines, since pumping has stopped in the nineties. The largest event in the swarm of 2000-2002 (M = 3,9) caused damage to buildings in the city of Voerendaal (broken chimneys, cracks in walls). The region has a moderate level of hazard due to natural seismicity. The effects of possibly induced events contribute marginally to the, naturally existing seismic hazard and risk.

<u>Need for knowledge: Moderate</u>

In the interpretation of the causes of possibly induced seismicity in the south of the Netherlands a detailed model of the deep subsurface is lacking. This is essential for the understanding of processes involved.

<u>Need for risk/hazard tools: Moderate</u>

A moderate extension of the monitoring around potential locations of induced earthquake activity (e.g. Voerendaal) will help in investigating the cause of the swarms and, therefore, the occurrence of possible future swarms. The availability of an improved subsurface models is essential.

<u>Need for protocols: Moderate</u>

Generally accepted and embedded tools for seismic monitoring including QA and governance.

3.7.2 Surface deformation

The heat map in Figure 3-18 summarizes the state of play regarding surface deformation hazard development and assessment for coal mining in the Netherlands.

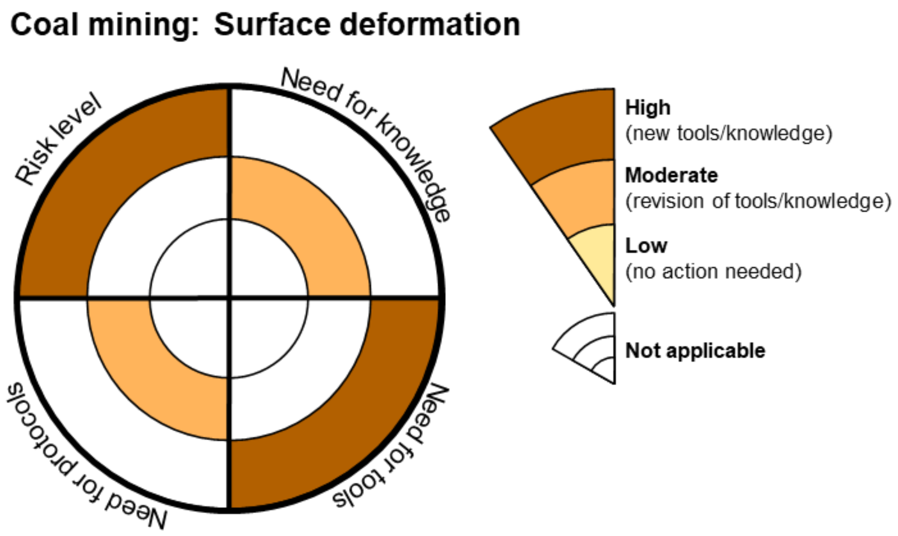

Figure 3-18: Circular heat map describing the status and assessment requirements for surface deformation hazards in coal mining

Risk level: Moderate

In southern Limburg a gradual rise of the surface level occurs as a result of rising mine water levels (swelling of the soil and pressure build-up in subsurface mine workings). Until 2014 a rise of max. 30 cm has been measured, which is 3% of the locally maximum 10 m subsidence that occurred during mining. There are seven confirmed cases of damage to houses due to differential uplift between 2009 and 2013. Differential deformation in Zuid-Limburg may also be related to several near surface faults (e.g. Heerlerheide breuk/Feldbiss).

Additionally, abrupt subsidence can take place at older (poorly abandoned) or very shallow (<100m) mine workings that were mined before 1960. The main cause is flushing of filling materials and consequential collapse of mined panels. Rising mine water can also trigger this hazard. Mine workings that were excavated and closed in the period between 1960 and 1974 have been reinforced with concrete plates. Here the risk of collapse is smaller. In 2011 a sinkhole developed as result of a caving process (formation of a chimney) which extended from a corner point of a coal panel (mine working).

The rising mine water level is expected to reach its highest level in the next 20-40 years.

GS-ZL (2016) [14]concludes that the effects of differential surface movements caused by rising mine water are limited to three areas (Geleen near the Heerlerheide Fault, Brunsum and Eygelshoven near the Feldbiss Fault). Small damages to buildings

[14] Roest, Kragten, Witteveen&Bos, 2018. Risicosignalering na-ijlende effecten steenkoolwinning
GS-ZL, 2016. Na-ijlende gevolgen steenkoolwinning

may occur yet big damages are not expected. Risks for special buildings or sensitive infrastructure with specific stability demands are not investigated.

Need for knowledge: Moderate
Surface instability is a major concern in some old coal mining areas. Research questions relate to better understanding of irregular surface movement (due to rising mine water), and mitigation/prevention of collapse.

Additional knowledge is needed to understand the potential impacts of smaller upward drillings (placed from upper mining levels to detect the position of the Top Carboniferous). These wells may act as conduits for sand displacement and soil dissolution.

Need for risk/hazard tools: High
There is a need for improved monitoring capabilities for abandoned coal mines and solutions for stabilizing old mines at risk. Accurate risk contours should be established for abandoned mine workings at risk. Furthermore, an Early Warning System for surface movements is recommended. A basis for such warning and risk management system is elaborated in GS-ZL 2016 and Roest et al.[14]

Need for protocols: Moderate
The issue and risk of collapsing mine workings are pressing concerns in specific regions (e.g. collapses and damaged to buildings in Heerlen). Protocols should focus on prevention of further damage (e.g. monitoring old mine workings at risk with early warning system) and mitigation of possible impacts (e.g. filling holes as they start to develop).

3.7.3 *Leakage and migration*

The heat map in Figure 3-19 summarizes the state of play regarding leakage and migration hazard development and assessment for coal mining in the Netherlands.

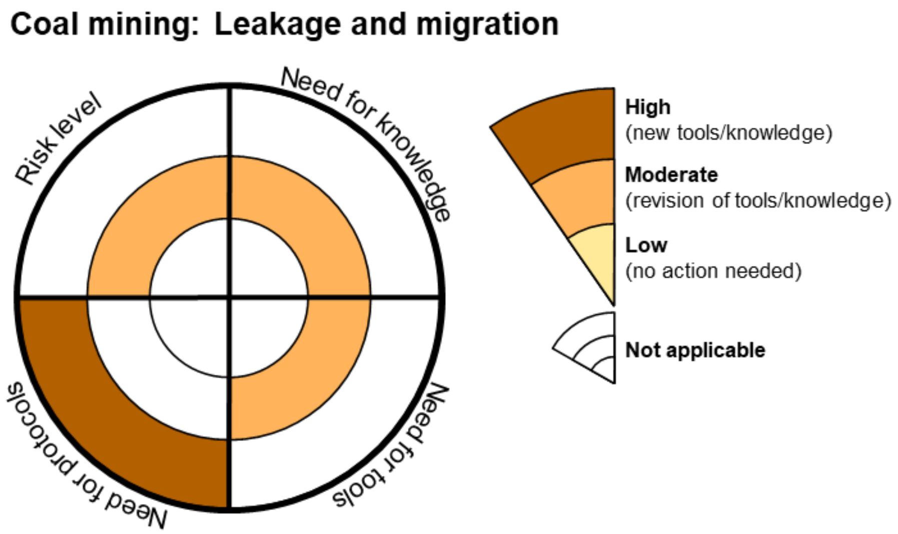

Figure 3-19: Circular heat map describing the status and assessment requirements for leakage and migration hazards in coal mining

Risk level: Moderate
After the coal production ceased, groundwater started rising and this process is still progressing. The groundwater is expected to reach its hydraulic equilibrium in 20-40 years from now (~2050). Groundwater rises increases pressures in old mine workings, likely leading to a mixing of polluted mine water and pristine groundwater. The increasing pressures may also result in the escape of mine gases present in mined panels, these gasses could accumulate in cellars and other closed structures. Furthermore, rising groundwater leads to increased wetting of nature and agriculture areas and cause inundation of cellars and affect structures. It is expected that damage to buildings or nature will be limited

The risk level is classified as moderate because the potential negative consequences are localized and have been largely identified as a nuisance.

Risks concerning mine gas could be severe and need active monitoring of those sites that have a natural vulnerability.

Need for knowledge: Moderate
On a regional scale the effects of the rising ground water have been identified and reported. However, there are two issues that need attention. Frist the impacts of the rising groundwater are locally, and the regional approach lacks the resolution to identify the actual buildings/structures at risk. Finally, the processes associated with the rising groundwater are not well understood and need attention to improve the capabilities to assess the actual risks till the hydraulic equilibrium will be reached.

In addition, it has been advised to have a monitoring program for the region, for groundwater levels and ground water quality.

Need for risk/hazard tools: Moderate
There is a need for improved monitoring capabilities for the region. Accurate risk contours should be established for those sites at risk. Generally accepted ensemble of tools with QA and maintenance cycles, formally. implemented in commissioned investigations.

Need for protocols: High
The issue of rising groundwater is a pressing concern for specific parts in the region. Protocols should focus on prevention of damage and health risks (e.g. solutions for gas accumulation) and mitigation of possible impacts. Protocols should be site and case-specific. A generic tool for risk management has been developed in 2018[15] including a measurement and action protocol plus dashboard (groundwater, surface deformation, mine gas escapes)..

3.7.4 *Facility hazards*

The heat map in Figure 3-20 summarizes the state of play regarding facility hazard development and assessment for coal mining in the Netherlands.

[15] Roest, Kragten, Witteveen&Bos, 2018. Risicosignalering na-ijlende effecten steenkoolwinning.

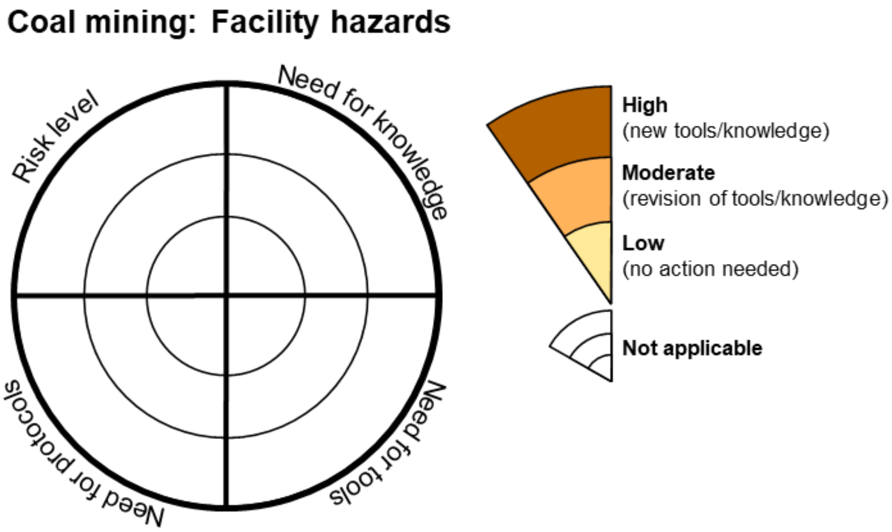

Figure 3-20: Circular heat map describing the status and assessment requirements for facility hazards in coal mining

<u>Risk level: Not applicable</u>
Mining activities have ceased and are not expected to take place in the future.

<u>Need for knowledge: Not applicable</u>
Coal mining activities have ceased in the Netherlands and production infrastructure has been abandoned and decommissioned.

<u>Need for risk/hazard tools: Not applicable</u>
Coal mining activities have ceased in the Netherlands and production infrastructure has been abandoned and decommissioned.

<u>Need for protocols: Not applicable</u>
Coal mining activities have ceased in the Netherlands and production infrastructure has been abandoned and decommissioned.

3.8 Synthesis

The table below summarizes the outcomes of the circular heat maps into one overview. The color legend is similar to those used in figures of paragraphs 3.3 to 3.7. The codes in the various cells discriminate between different asset types within the given category of mining activities. The abbreviations are explained below.

Category		Risk level	Need for		
Mining activity	**Hazard**		**Know-ledge**	**Tools**	**Proto-cols**
Oil and Gas	Seismicity	gro / oth	gro / oth		
	Surface deformation				
	Leakage and migration				
	Facility	off / on		off / on	off / on
Geothermal	Seismicity	std / udg			
	Surface deformation				
	Leakage and migration				
	Facility				
Storage And Injection	Seismicity				
	Surface deformation				
	Leakage and migration		hyd / ugs	oth / ugs	oth / ugs
	Facility	hyd / ugs	oth / ugs		oth / ugs
Salt Mining	Seismicity				
	Surface deformation				
	Leakage and migration				
	Facility				
Coal Mining	Seismicity				
	Surface deformation				
	Leakage and migration				
	Facility				

Table 3-2: Overview of state of play and ranking of urgent issues for the strategic agenda. Ranking and legend explained in paragraphs 3.3 to 3.7.

gro = Groningen
oth = other gas fields (oil/gas) / other storage technologies (storage)
on = onshore
off = offshore
std = standard geothermal doublet
udg = ultra-deep geothermal
ccs = carbon capture and storage
hyd = hydrogen storage

From Table 3-2 it can be concluded that the following aspects are pivotal from a pure technical point of view (acknowledged hazards, need for knowledge and tools):

- Seismicity: gas production (induced by depletion and compaction) and geothermal (triggered by water injection)

- Surface deformation: salt mining and coal mining (both related to long term, post abandonment effects). Also consider the possible occurrence of unexpected hazardous events (to be identified with scenario analysis) which would require additional monitoring.

- Leakage and migration: oil/gas production, storage/injection (well integrity and abandonment), salt mining (abandonment of caverns), coal mining (rising mine water)

- Facility hazards: Mainly new some new (immature) types of storage

4 Inventory of mining risk tools

4.1 Introduction

The main objective of the risk toolbox platform is to establish a framework for development, maintenance, validation and dissemination of (certified) tools used to assess and manage risks related to mining activities. This chapter briefly evaluates the currently known mining risk and hazard tools.

Generally, the Risk Bow-Tie methodology can be regarded as an important tool for all combinations of mining activities and related effects, hazards and impacts. In the context of this study however, the bow-tie is also seen as a framework in which the presented tools are positioned with regards to their purpose and field of application. A model train as developed for Groningen for example, represents the entire bow-tie including hazard, prevention measures, the event itself, the impacts and the mitigating measures. Other tools only focus on one specific area of the bow-tie.

One of the key challenges is, how can the interfacing between tools in different areas of the bow-tie be improved? If done properly, this will open the way to turn the focus from hazard assessment to a more mature management of risk.

4.2 General inventory of risk tools

Annex A lists all tools that have been inventoried for this study. The list incorporates 106 tools in total. The most important tools are described in further detail in Paragraph 4.3. The figures below provide a brief analysis of the tool status, functionalities and application areas.

Figure 4-1 evaluates the distribution of assessed tools across the main hazard categories (seismicity, surface deformation, leakage, facility hazard, general risk management), subdivided by a) mining category and b) type of tool. Note that a tool may belong to multiple categories (e.g. it may be applicable to oil/gas and geothermal)

Figure 4-1a reveals that most tools included in the table are apparently developed for seismic hazard analysis in relation to oil and gas production. Within this category there is a fair balance in the distribution of tools across the various risk assessment components (i.e. source data, path-site response, impact-fragility and validation data). This is also reflected by the inclusion of two model trains (NAM and TNO) that both provide a composite tool kit for an integrated assessment of seismic hazards and impacts.

The other prominent category is leakage hazard. Most of these tools represent source data for production behaviour, path-site response (e.g. fluid migration and transport in ground water) and validation data (e.g. permeability, water properties, reactivity, etc.).

Tools related to coal mining as well as facility hazards are clearly under-represented in the overview. The latter is probably related to the fact that these tools often have a limited relevance to subsurface processes, and thus have not been regarded during the inventory. The coal mining risks represent a location and case-specific issue which is investigated in dedicated projects and workflows.

A last, important observation is the limited availability of tools for determination of impacts (except for seismicity in gas production). This aligns with the general conclusion that many of the investigations focus on the assessment of hazard rather than the assessment of risk. Groningen is a clear deviation from that trend.

	gas/oil	geothermal	storage	salt	coal	general
Risk management			1			3
Seismicity	32	8		8		13
Surface deformation	8	2		2		9
Leakage	6	14	7	5	1	6
Facility hazard	1	1	1	1		2

a

	general	source	path - site response	impact - fragility	validation data
Risk management	4				
Seismicity	3	6	12	8	17
Surface deformation		2	13	1	3
Leakage	1	8	8	1	12
Facility hazard		2			1

b

Figure 4-1: summary of tool entries per hazard category, mining activity and type of tool

Figure 4-2 provides further insight in the origins of the tools included in the overview. There is a distinct bias towards tools that have been developed/owned by TNO. In its function as Geological Survey of the Netherlands (and the former State Geological Survey), this institute has a long track record in subsurface hazard research. TNO maintains the central registry for subsurface data and information, acting as one of the key advisors with regards to mining activities in the Netherlands. Many tools have been developed to support this role. Deltares governs a broad selection of tools that relate to migration of contaminants and groundwater flow resulting from leakage and surface deformation. These tools are applied in many national and site-specific hazard studies. KNMI specifically focuses on seismicity tools (e.g. registration of earthquakes). Tool from other organizations are predominantly focused on seismicity and gas production.

	g as/oil	geothermal	storage	salt	coal	general
TNO	19	8	3	2		14
Deltares	5	6	3	2	1	8
KNMI	4	3		4		
Other - NL	5	1	1	1		2
Other - international	14	7	2	7		9

a

	Risk management	Seismicity	Surface deformation	Leakage	Facility hazard
TNO	2	19	12	11	
Deltares	2	3	4	8	1
KNMI		4			
Other - NL		5		2	1
Other - international		15	3	9	1

b

Figure 4-2: summary of tool entries per owner/developer, mining activity and hazard category

Figure 4-3 shows what platforms are used for tools development and what are the access regimes. Approximately 50% of the tools is available as open source or freeware components. For the rest, access is mainly restricted and licenced. Most tools are defined as source code and scripts or as extensions for commercial and open source software packages. Furthermore, data and methods also widely recognized as tools for hazard research.

	Instruments	Data - methods	Source code - script	Software - Extensions	Web - portal
Risk management		4			
Seismicity	2	5	23	15	1
Surface deformation	2	1	8	8	
Leakage	2	11	10	5	2
Facility hazard	1			2	

	Confidential	Restricted / Licence	Open / Freeware
Risk management	1	1	2
Seismicity	1	26	19
Surface deformation		9	10
Leakage	2	8	20
Facility hazard		2	1

Figure 4-3: summary of tool entries per hazard category, tool platform and tool access regime

4.3 Risk tool assessment and state-of-art

The following sections provide a description of a selection of most important tools used for risk assessment and policy support. The selection was determined by TNO, Deltares and KNMI, based on their experiences and role in hazard and risk assessment. For each tool a summary of functionality and quality assurance requirements is presented

4.3.1 Seismicity tools

KNMI National seismic risk model validation data network:		
Owner/developer: KNMI	**Maintenance:** Regulated, national program	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Low	**Nature of tool:** Data acquisition
Description: Monitoring system for seismic events. Dedicated seismometers are located near producing gas fields and storage sites. A dense network is available in Groningen. The accuracy of earthquake localization partly depends on the density of seismometers		
Application: Generic for seismicity		
Quality assurance: The maintenance and deployment of the seismic monitoring and data network is formally governed by KNMI. The tool is part of the TNO seismic risk model train for risk assessment (validation data). Quality assurance is being elaborated through this model.		
Tool functionality: The distribution of seismometers is regularly extended. It is recommended to expand the network at geothermal doublets.		

NAM Groningen seismic risk model train		
Owner/developer: NAM	**Maintenance:** Operator	
Maturity/ TRL: 9 Operational, proven	**Complexity:** High	**Nature of tool:** Composite model train
Description: Model train for seismic hazard, building damage and (personal) risk assessment for Groningen gas field production plan. The model train comprises of sequential coupling of a Seismological Source Model, a Ground Motion Model and a Damage Model.		
Application: Groningen gas field		
Quality assurance: The methodology of the model components is described in several peer reviewed scientific papers. Maintenance of the model train software is executed by the operator.		
Tool functionality: Operator is in the process of making the software code available for review to State Supervision of Mines. Further future development is limited.		

TNO Groningen seismic risk model chain		
Owner/developer: TNO	**Maintenance:** Project, EZK/KEM program	
Maturity/ TRL: 7 Implementation, prototype operational testing	**Complexity:** High	**Nature of tool:** Composite model train
Description: The effect of gas production on building damage and associated risks can evaluated with use of the TNO implementation of the Groningen seismic risk model train. This model train is a stand-alone development, independent from the NAM Groningen model train. It is intended to incorporate and interface to tools from various institutes including KNMI and Deltares.		
Application: Groningen gas field		
Quality assurance: Industry standard software quality assurance are adopted for reproducibility and traceability of model results. These standards have been extended with tailored and fit-for-purpose QA elements.		
Tool functionality: Externally developed model components can be plugged into the model chain. The integration of different tools is achieved through standardized application interfaces. Alternative seismic source models are currently in development. Publication and dissemination of the model train are currently under evaluation.		

Seismic risk protocol for small gas and oil fields		
Owner/developer: SodM	**Maintenance:** Regulated, national program	
Maturity/ TRL: 7 Implementation, prototype operational testing	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: SODM protocol for addressing, preventing and mitigating seismic hazards/risk in oil/gas production.		
Application: Gas production (general)		
Quality assurance: Mature seismic risk protocols are in place and generally accepted by the industry.		
Tool functionality: The existing protocols are under development by SodM as new information has become available.		

Geomech: Excel injection pressure tool		
Owner/developer: TNO	**Maintenance:** Regulated, national program	
Maturity/ TRL: 7 Implementation, prototype operational testing	**Complexity:** Low	**Nature of tool:** Model, function
Description: An Excel calculation sheet for determining the relation between injection pressure and multiple gradients: injection pressure gradient SodM, lithostatic pressure gradient, hydrostatic pressure gradient, minimal horizontal stress gradient (Shmin), thermal effects of injected water on reservoir rock (Shmin-thermal)		
Application: Geothermal projects		
Quality assurance: The tool does not have a formal quality assurance procedure. Given the low business risk and simple analysis, a “Version control” and “Analyst-led” quality assurance procedure. Proper documentation needed when the tool will be publicly disseminated.		
Tool functionality: It is recommended to regularly review whether new gradient functions should be added.		

Seismic hazard and risk protocol for geothermal		
Owner/developer: SodM	**Maintenance:** Regulated, national program	
Maturity/ TRL: 7 Implementation, component testing	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: SODM protocol for addressing, preventing and mitigating seismic hazards/risk in geothermal production is currently under development. A protocol is in place with respect to maximum allowed injection pressure.		
Application: Geothermal projects		
Quality assurance: There is no formal framework for development and maintenance of tools available yet.		
Tool functionality: The protocol is under development.		

4.3.2 Surface deformation tools

ESIP (Ensemble-based Subsidence Interpretation and Prediction)		
Owner/developer: TNO	**Maintenance:** Project	
Maturity/ TRL: 8 Operational, demonstration	**Complexity:** High	**Nature of tool:** Composite model train
Description: Full composite model for interpretation and prediction of subsidence due to mining activities.		
Application: Mainly subsidence due to gas production, Wadden Sea		
Quality assurance: Methodology and manual available. Peer reviewed paper on methodology pending.		
Tool functionality: Development towards scalability of the level of complexity to use this tool for less complex subsidence cases.		

INSAR surface deformation computation		
Owner/developer: TU-Delft	**Maintenance:** Program	
Maturity/ TRL: 7 Implementation, component testing	**Complexity:** Average	**Nature of tool:** Data processing and interpretation
Description: Satellite observation, data-processing and computation of surface deformation.		
Application: Generic for surface deformation		
Quality assurance: Focused on the comparison with similar, alternative measurements (levelling, GPS) and related uncertainties. To be used as a validation tool.		
Tool functionality: Mainly focused on the quality control of signal and measurement analyses. Developing towards a real-time monitoring tool.		

Reservoir compaction to subsidence influence function		
Owner/developer: TNO	**Maintenance:** Regulated, project	
Maturity/ TRL: 8 Operational, demonstration	**Complexity:** Low	**Nature of tool:** Empirical model
Description: Fast models to estimate subsidence resulting from reservoir compaction (e.g. linear, time-decay and rate-type compaction). Most widely used -and extended- is the *Geertsema* formulation. In addition to that other models like the *van Opstal* and *Knothe* (Gaussian) are available.		
Application: Gas production, small fields		
Quality assurance: Mature calculation methodology and commonly accepted by the industry.		
Tool functionality: Drawback of fast models is their applicability to complex, heterogeneous reservoirs.		

DIANA modelling environment		
Owner/developer: TNO/DIANA FEA	**Maintenance:** Commercial	
Maturity/ TRL: 9 Operational, proven	**Complexity:** High	**Nature of tool:** Finite element model
Description: Commercial finite element analysis solver.		
Application: Generic for surface deformation		
Quality assurance: The industry standard software package for structural and geotechnical engineering.		
Tool functionality: Software package is actively developed towards market needs.		

4.3.3 Leakage and migration tools

DIANA modelling environment		
Owner/developer: TNO/DIANA FEA	**Maintenance:** Commercial	
Maturity/ TRL: 9 Operational, proven	**Complexity:** High	**Nature of tool:** Finite element model
Description: Commercial finite element analysis solver.		
Application: Generic for surface deformation		
Quality assurance: The industry standard software package for structural and geotechnical engineering.		
Tool functionality: Software package is actively developed towards market needs.		

STOMP groundwater models		
Owner/developer: PNNL	**Maintenance:** Program	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: STOMP is a computer model, designed to be a general-purpose tool for simulating subsurface multifluid flow and transport. STOMP's target capabilities were guided by proposed or applied remediation activities at sites contaminated with volatile organic compounds and/or radioactive material.		
Application: Generic for groundwater flow		
Quality assurance: Software application is documented. Applied methodologies are published in peer reviewed scientific journals.		
Tool functionality: There is a desire for coupling with other models (e.g.: iMOD)		

iMOD groundwater models		
Owner/developer: Deltares	**Maintenance:** Program	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Low	**Nature of tool:** model
Description: iMOD is a high performance MODFLOW clone for groundwater flow modelling.		
Application: Generic for groundwater flow		
Quality assurance: Well documented open source software.		
Tool functionality: There is a desire for coupling with other models (e.g.: STOMP)		

Thermal fraccing tool		
Owner/developer: TNO	**Maintenance:** Project	
Maturity/ TRL: 7 Implementation, component testing	**Complexity:** Low	**Nature of tool:** model
Description: … (binding with STOMP)		
Application: Geothermal		
Quality assurance: Internal		
Tool functionality: Improve end-user functionality		

Mod path groundwater models		
Owner/developer: USGS	**Maintenance:** Regulated	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: MODPATH is a particle-tracking post-processing model that computes flow paths using output from MODFLOW.		
Application: Generic for groundwater flow		
Quality assurance: Well documented open source software.		
Tool functionality: …		

SEAWAT groundwater models		
Owner/developer: USGS	**Maintenance:** Regulated	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: SEAWAT is a generic MODFLOW/MT3DMS-based computer program designed to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport.		
Application: Generic for groundwater flow		
Quality assurance: Well documented open source software.		
Tool functionality: …		

MT3D groundwater models		
Owner/developer: USGS	**Maintenance:** Regulated	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: A three-dimensional (3D) multispecies contaminant transport model with a modular structure to permit simulation of solute transport processes independently or jointly.		
Application: Generic for groundwater flow		
Quality assurance: Well documented open source software.		
Tool functionality: …		

Cassif-FEP		
Owner/developer: TNO	**Maintenance:** Program	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Low	**Nature of tool:** Data visualization
Description: A scenario analysis framework based on the three major CO2 release scenarios (well, fault and seal) from where the relevant events and processes are identified and modelled. Expert opinion is a key value within this framework. The framework provides speed, transparency and comprehensiveness in the creation of subsurface CO2 release scenarios.		
Application: CO2 storage		
Quality assurance: Software application is documented. Applied methodologies are published in peer reviewed scientific journals.		
Tool functionality: …		

Mirecol Web App		
Owner/developer: TNO	**Maintenance:** Project	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: Web based application serving as a reference for CO2 storage operators, regulators, authorities, decision makers, and the public to learn more about remediation measures available in the case of undesired CO2 migration. The tool is intended to aid the research process and does not replace creating a remediation or contingency plan.		
Application: CO2 storage		
Quality assurance: Software application is documented. Applied methodologies are published in peer reviewed scientific journals.		
Tool functionality: …		

PHT3D		
Owner/developer: CSIRO	**Maintenance:** ..	
Maturity/ TRL: 8 Operational, demonstration	**Complexity:** Low	**Nature of tool:** Data acquisition
Description: PHT3D is a multicomponent transport model for three-dimensional reactive transport in saturated porous media. It's a combination of PHREEQC and NT3DMS.		
Application: CO2 storage		
Quality assurance: Methodologies and applications published in peer reviewed scientific journals.		
Tool functionality: …		

PHREEQC		
Owner/developer: USGS	**Maintenance:** Regulated	
Maturity/ TRL: 9 Operational, proven	**Complexity:** Average	**Nature of tool:** Process-driven model
Description: Software to perform a wide variety of aqueous geochemical calculations.		
Application: Ground water flow		
Quality assurance: Well documented open source software		
Tool functionality: There is a desire for coupling with flow simulators / models		

5 Blueprint for a national risk toolbox

5.1 Introduction

In the context of the proposed national risk toolbox, tools are defined as:

- Instruments, e.g. used for monitoring of effects and impacts
- Datasets used for risk assessment and tool/model validation (e.g. obtained from subsurface acquisition and monitoring campaigns)
- Models and analyses describing subsurface and risk processes (e.g. deterministic, stochastic, empirical, process-based)
- Software and methods used to analyse effects, risks and impacts (e.g. stand-alone software, user scripts, functions)
- Composite model trains defining a linked chain of (compatible) datasets, models and scripts for a more comprehensive assessment of effect, risk and impact
- Protocols and guidelines prescribing preferred or mandatory practices and standards for risk assessment

Currently there is no platform available for the development and administration of mining hazard and risk assessment tools in the Netherlands. Tools are often developed within individual projects or they are components of established (in-house) workflows. Some tools represent stand-alone commercial software packages, on top of which specific scripts have been developed. Other tools are developed from ground up using various programming languages. All in all, there is a lack of standardize interfaces hampering an efficient linkage of tools which may be needed to establish a complete event-to-impact assessment workflow. Furthermore, tools often embed their own validation and (peer-) review procedures. Consequently, there is no formal process which assures the quality and development cycle of all relevant tools in a standardized manner. Last but not least, tools developed under projects or other temporary processes are generally lacking the means (finance, governance structure) for sustainable and long-term maintenance.

Over the past five years, the focus on mining hazards and risks has intensified. Since the Huizinga earth quake and the advice of the OVV (National Safety Research Council), the Groningen gas field has been subjected to extensive hazard and risk evaluations. These investigations have led to the development of an integrated risk modelling and assessment process which is now represented by the NAM seismic risk model train[16]. A comparable and independent seismic risk model train has been developed by TNO (with involvement of KNMI and Deltares). The latter model train has been realized through standardization and re-engineering of existing tools into compatible components that are combined to integrally assess the influence of various production profiles on seismic risks and impacts. For the Groningen model train, TNO has implemented international quality assurance standards and guidelines as reported in the Aqua Book (HM Treasury, 2015) and the Quality Assurance Guidance for Models (DECC, 2015).

[16] NAM 2016, Study and Data Acquistion Plan for Induced Seismicitiy for Winningsplan 2016

The evolution of seismic risk in Groningen is not the only reason to review the current set of risk assessment tools and instruments. New types of mining activities (e.g. geothermal production, subsurface storage) are emerging in the Netherlands. These activities have specific risk profiles which require tailored assessment tools (see Chapter 3). A national risk toolbox provides the technical framework (in conjunction with the strategic research agenda) to steer the development of these tools and to facilitate the deployment through supporting information and user/developer guidelines.

This chapter presents the outlines and recommendations for the development of a national risk toolbox for mining hazards and risks. Chapter 6 details the implementation of standard and proportional quality assurance guidelines for the development and maintenance of certified risk tools.

5.2 Soil and Groundwater Risk toolbox: an example

RIVM (National Institute of Public Health and the Environment) governs a national soil and groundwater risk toolbox linked to the policy framework of contaminated site management in the Netherlands[17]. This toolbox is accessible through the portal "www.risicotoolboxbodem.nl". This platform incorporates and explains the certified instruments supporting legal tasks related to the soil quality policy and the governmental note on soil remediation.

The major risk assessment tools in The Netherlands are the CSOIL exposure model (human health risks and food safety), Species Sensitivity Distributions and the Soil Quality Triad (ecological risks), along with a procedure to assess the risks due to contaminant spreading to and in the groundwater[17]. Tiered approaches are used to assess risks and mitigation measures. These approaches are supported via the toolbox with web-based decision support systems.

The soil and groundwater risk toolbox is assumed relevant for the proposed mining risk toolbox in the following ways:

- The soil and groundwater risk toolbox represents a concrete example of how risk tools can be deployed through a web-portal. Access to these tools can be obtained through a registration procedure and includes all relevant documentation. The tools are linked to legal tasks.
- The risk assessment follows a flexible and tiered fitness-for-use approaches according to the principle 'simple if possible, complex when necessary (Figure 5-1). The presentation and implementation of such a tiered approach may serve as an effective guidance instrument for (regional) policy makers and stakeholders dealing with mining risks.
- Mining activities may pose a contamination risk on soil and groundwater (i.e. source of contamination). This relationship raises the question whether how both risk toolboxes should be linked.

[17] Swartjes, F.A., M. Rutgers, M., Lijzen, J.P.A., Janssen, P.J.C.M., Otte, P.F., Wintersen, A., Brand, E., Posthuma L., 2012. State of the art of contaminated site management in The Netherlands: Policy framework and risk assessment tools

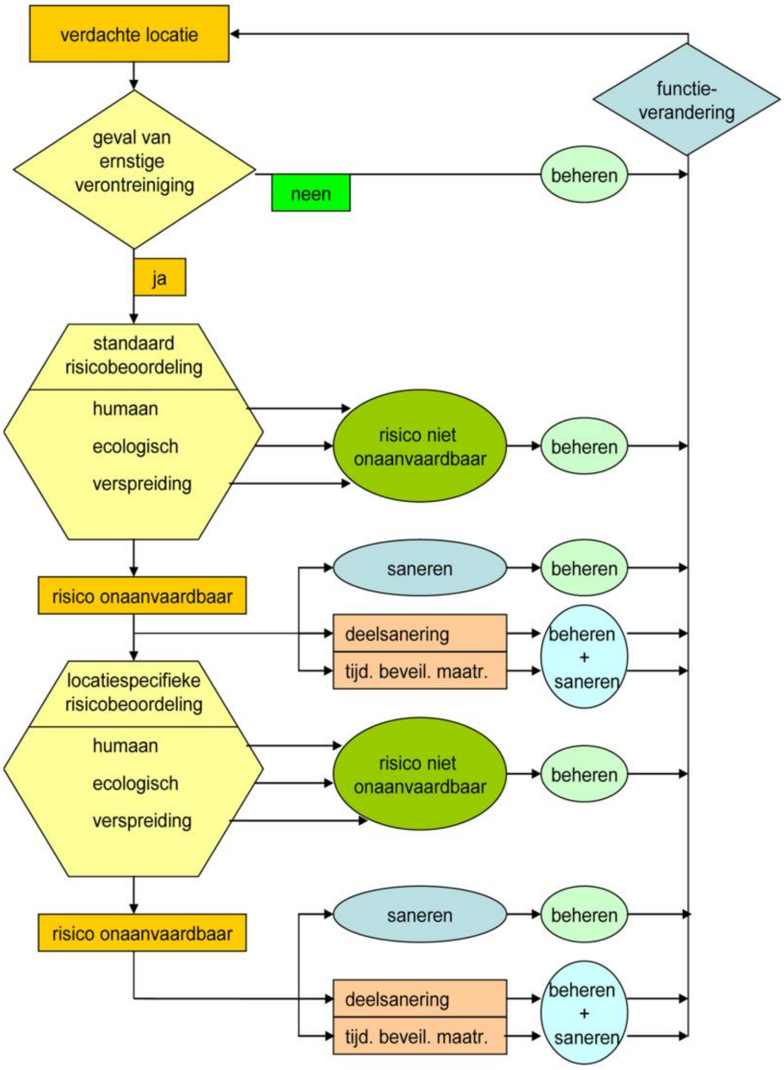

Figure 5-1: Example of a tiered approach used for contaminated site management and risk assessment (Circulaire bodemsanering, Staatcourant nr. 16675, 23 juni 2013)

5.3 Proposed mining risk toolbox functionalities

The following sections introduce some key qualifications and functionalities that are proposed for the national risk toolbox for mining hazards and risks:

5.3.1 Centralized storage and administration of tools:

One of the basic functionalities of the risk toolbox is to set up a centralized administration of risk tools. This administration can be achieved through the set-up of a meta-data archive which provides descriptive and administrative information regarding the tools, including:

- Tool identification: (name and description, field of application, type, functionality, platform, etc.)
- Tool status: (maturity and development, version, revision history, etc.)
- Tool quality: (QA, certification, etc.)
- Tool source: (identification of owner/developer, funding and maintenance program, project, etc.)

- Tool access: (user/access rights, location/repository where the tool / source code can be accessed, restrictions and conditions, etc.)
- Tool documentation: Reference to documentation, user guides, scientific publications, etc.
- Set up a QA process of the meta-data: a regular (yearly) process to validate availability and correctness of all the meta-data information.

There are various standards for the registration of metadata (e.g. Directory Interchange Format[18], Metadata Encoding & Transmission Standard[19]). It is recommended to evaluate these standards on their applicability and functionality.

5.3.2 *Improved consistency in risk assessment:*

Besides being a repository of tool information, the risk toolbox may serve as a platform for establishing standards and development protocols that allow for a better alignment of tools and their outcomes. Some examples are:

- Standards for hazard and risk classification, quantification and representation. This will help to improve comparison, validation, archiving and reproduction of risk assessment outcomes.
- Development of tool interfaces, eventually supported by common file formats, application programming interfaces and libraries to facilitate tool integration.
- Stimulate the development of composite model trains for selected and relevant mining activities and risk categories (e.g. similar to ESIP[20], Groningen seismic risk model train)

It is recommended to discuss and define above standards through a dedicated user and developer community that is linked to the risk toolbox platform.

5.3.3 *Standardized quality assurance procedures:*

Quality Assurance (QA) is a critical aspect for the development and maintenance of certified and validated tools. QA determines the maintenance of a desired level of quality in a service or product, especially by means of attention to every stage of the process of delivery or production.

It is recommended to implement a standardized quality assurance (QA) procedure for the development and maintenance of certified risk tools. The basis for the QA model should be provided through internationally accepted standards, which are then tailored for the use in the mining risk toolbox (see Chapter 6). The level of QA for a tool within the toolbox should depend on the risk associated with the intended use of the tool and on the complexity of the tool. As a starting point, it should be decided which tools are considered for a QA procedure and what level of QA is needed.

5.3.4 *Link with the national (strategic) research agendas:*

The various research agendas initiate and coordinate new scientific developments that may require a translation into new or adapted risk tool functionalities. The toolbox should provide the supporting framework to implement and deploy these functionalities (e.g. through a formal quality assurance cycle for development, common agreed standards, integration with other tools and model trains, etc.).

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[18] https://gcmd.gsfc.nasa.gov/DocumentBuilder/defaultDif10/guide/index.html
[19] https://www.loc.gov/standards/mets/
[20] TNO 2017, Ensemble-based Subsidence Interpretation and Prediction ESIP: Technical Reference Manual. TNO Report R11278

Secondly the risk toolbox is considered to act as a common platform for the regular inventory of tool deficiencies and missing functionalities. These reported issues, on their turn, may lead to the definition of new research questions addressed by the research programs.

It is recommended to establish a communication and coordination structure which governs this two-way transfer of information between the research agendas and the risk toolbox.

5.3.5 Facilitate embedding and deployment of risk tools:

The deployment of risk tools is mostly reserved to skilled experts. Yet, from a stakeholder point-of-view, there is a growing demand for transparency and insight regarding the procedures and protocols to be followed in risk assessment as well as the tools and solutions that are required and available for certain situations. This concerns for example policy makers and regulators who are responsible for risk management and supervision.

The toolbox provides general information about the various procedures and protocols that need to be followed in risk assessment. Furthermore, it could recommend the use of preferred workflows and certified tools depending on the type of mining activity and the definition of the risk. Like the soil and groundwater risk toolbox (Paragraph 5.2), this may be achieved by defining tiered, fitness-for-use approaches and decision-support schemes. In a more advanced approach, the toolbox could offer a user interface to directly run certain tools themselves.

It is recommended to establish a user-community consisting of various stakeholders and end-users. This community can be consulted on the quality and functionality of the toolbox as well as new, essential functionalities to be implemented.

5.4 Provisional roadmap for development and maintenance

This report delivers a first provisional roadmap for the development of the risk toolbox. This roadmap still needs to be further elaborated and approved by a detailed development plan. The following sections briefly outline the various phases and activities foreseen for the risk toolbox development and implementation in the coming four-year period. Figure 5-2 dives a provisional schedule of these phases in time.

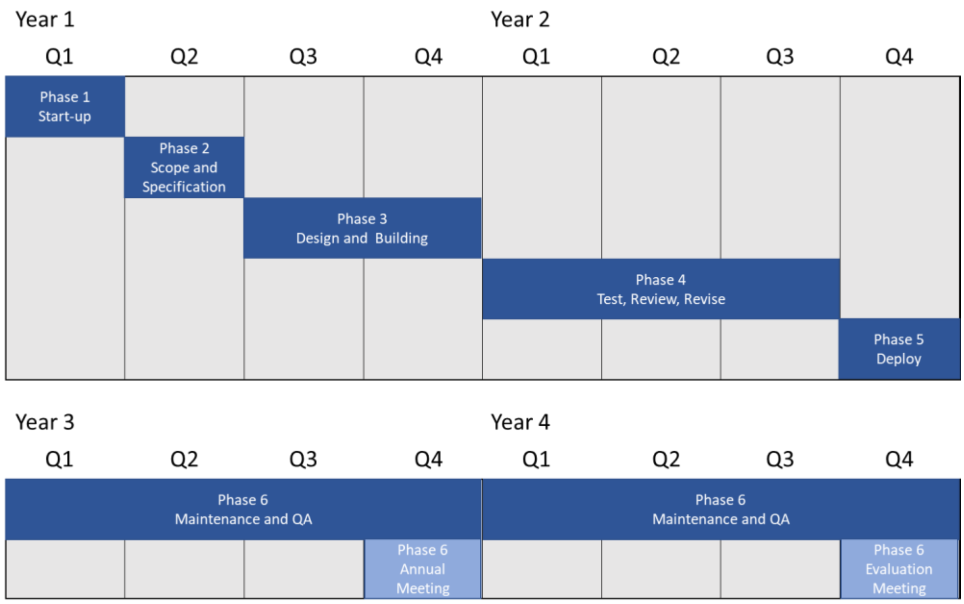

Figure 5-2: Provisional schedule of development and implementation phases for the risk toolbox platform. Development takes place in year 1 and 2. Implementation takes place in year 3 and 4.

5.4.1 Phase 1. Implement coordination structure for platform development

This phase concerns the preparatory steps for the risk tool development (workplan) and the establishment of the governance structure. The following aspects should be addressed:

- Coordination and stewardship:
  Installment of a project consortium consisting of TNO, Deltares and KNMI who will coordinate the development of the risk toolbox platform and maintenance procedures. The main responsibility and stewardship will be assigned to TNO.

- Steering committee
  Selection and assignment of a steering committee which incorporates representatives from MEA, SodM, KEM, and other key organizations who have a coordinating role in (national) mining risk assessments, risk management and supervision of mining activities. The steering committee acts as an advisory body for the development and implementation of the risk toolbox and is expected to convene on a regular basis during the development and implementation phase. SodM and/or MEA are the accountable and commissioning entities.

- User and developer communities:
  Selection and assignment of a user community consisting of key representatives from mining operators, consultants and end-users involved in mining risk/hazard assessment and management as well as a separate developer community of tools represented in the national risk toolbox. The user group will be consulted for technical advice regarding functionality requirements and operational aspects of the risk toolbox platform. The developer group should also be involved in determining toolbox architecture and the effectuation of the quality and assurance cycle.

- Work plan, communication strategy and kick-off:
  Before starting the development of the risk toolbox platform, the project consortium should elaborate a detailed workplan and communication strategy. These are to be presented and discussed during a kick-off workshop involving the steering committee and user group.

5.4.2 Phase 2. Elaborate scope and specifications:

This phase is focused on delivering a detailed specification for the envisioned risk toolbox contents and functionalities. These specifications should be established in collaboration with the user community and be approved by the steering community. The following activities are considered:

- Specification workshops:
  To obtain a complete overview of essential risk toolbox requirements, it is recommended to organize several workshops with relevant tool owners/developers and end-users
- Description of characteristics for selected tools:
  This action is intended to complete the list of available risk tools (including planned developments) and to complete all tool details relevant for the risk toolbox
- Definition of quality assurance procedures:
  Quality assurance is a vital element for the tool development and maintenance. This action aims to elaborate the QA aspects and to determine the level of QA required per tool.

5.4.3 Phase 3. Design and build initial platform for tool maintenance

This phase concerns the actual development of the first toolbox prototype. This version is proposed to deliver the following elements:

- Administrative framework for tool maintenance (i.e. metadata)
- Quality assurance system
- Online portal for tool information and dissemination
- Documentation and user guidelines

5.4.4 Phase 4. Platform prototype testing and reviewing

This phase focuses on the testing and reviewing the risk toolbox prototype by a selected group of developers and end-users. The following steps are considered:

- Preparatory workshops with user group:
  These workshops are held to inform the user community on the implemented risk toolbox contents and to explain the criteria and procedures for reviewing the functionalities
- Population of platform with selected tool information:
  The user community will select the tools that are included for the testing of the prototype.
- Platform testing:
  In this step the various functionalities of the toolbox are tested (e.g. tool access, QA cycle, communication and information)
- Review workshop with user group
  The findings of the user community are discussed and reported to the toolbox development team. The updates should be approved by the steering committee.

It is proposed to start the risk toolbox evaluation with the TNO Groningen model train for seismic risk assessment with the following arguments:

- The development and implementation of the TNO model trains is already planned, including an assessment and definition of quality assurance procedures required
- The model train comprises a subset of mature and established risk/hazard tools and will thus be suitable for testing mutual dependencies of tools in the risk toolbox
- The model train has great relevancy for current risks and impacts related to Groningen gas production. The model train is intended to be publicly disseminated

5.4.5 Phase 5. Platform deployment

After all proposed revisions and updates are implemented, the tool will be deployed to the broader public. This includes the set-up of a communication structure for end-users and stakeholders (e.g. information, questions and answers, feedback and suggested improvements, inclusion of new tools)

5.4.6 Phase 6. Implement risk toolbox maintenance and quality assurance cycle

After the deployment of the risk toolbox, it is recommended to regularly monitor the operation and experiences of the end-users and tool developers. The following events are proposed:

- Annual review meeting with steering committee to discuss alignment with the strategic research agenda (implementation of new tool functionalities following from the various research programs, propose research topics from observed gaps in tool functionality, decide on the yearly budget for tool development and toolbox maintenance)
- Annual or bi-annual meetings with the user community to discuss proposals for platform/tool revisions and maintenance procedures
- Final evaluation of risk toolbox by the steering committee and recommendations for continuation/follow-up

6 Quality Assurance

6.1 introduction

Quality assurance is the maintenance of a desired level of quality in a service or product, especially by means of attention to every stage of the process of development, utilization and support. Quality assurance provides decision makers with key information about how a risk tool or analysis works, as well as the associated risks and limitations, which are essential if tool and analysis outputs are to be used with genuine understanding and confidence.

It is recommenced to implement a formal quality assurance guideline for the proposed national risk toolbox for mining effects, based on published and widely accepted standards. The following sources on proper Quality Assurance were reviewed:

- *The Aqua book: guidance on producing quality analysis for government (2015)*. This is one of the products of the commissioned working group. It reviews and gives recommendations about quality assurance of analytical models across the UK government. It builds upon *Review of quality assurance of Government analytical models (2013)*.
- *Review of quality assurance of Government analytical models (2013)*. A commissioned review of the quality assurance of analytical models that inform UK government policy.
- *Quality Assurance: Guidance for Models (2015)*. A report from the Department of Energy & Climate Change (DECC). It is a guide that aims to clearly set out the steps required to QA both new and existing DECC models. It should be used to ensure that the model in question has been proportionally quality assured, with supporting documentation and evidence to demonstrate this.

In addition to this, the report draws from the experiences and guidelines established for the TNO Groningen Model Train (see Section 4.3.1). This complex aggregation of different risk/impact tools and connecting interfaces adopted the above standards, yet also included additional elements that are specific to the field of mining risk assessment and tool development. In this respect, it is advised to make the implementation of quality assurance proportional and fit-for-purpose to the tool complexity and the specific risk/impact being addressed.

The following sections explain the key aspects and recommendations for quality assurance. These should be further detailed and concretized once the toolbox itself is being developed.

6.2 Tool development cycle

Figure 6-1 represents the various phases and elements described for tool development. A tool can be a piece of software, a model or an analysis as defined in Paragraph 5.1. It is recommended to implement these steps at least for the development cycle of selected and certified tools in the risk toolbox, as well as for the development of the risk toolbox itself.

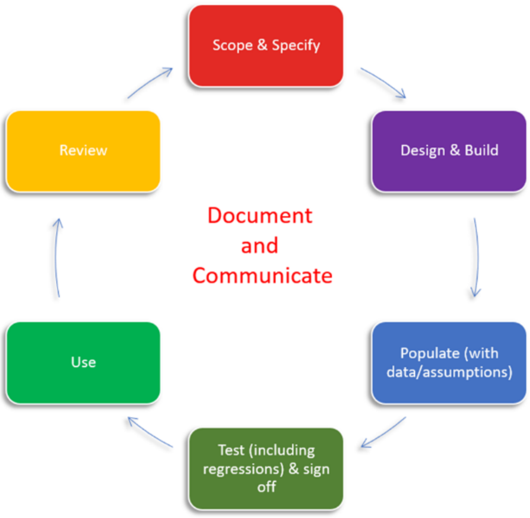

Figure 6-1: Visualization of the model cycle. Quality Assurance should be embedded within every step of the cycle. Source & adapted from Quality Assurance: Guidance for Models (2015)

The different steps of the cycle are:

1. **Scope and Specify**: Agree with the scope of the tool and turn that into a functional specification for the tool including an outline design
2. **Design and Build**: Design and build the tool
3. **Populate** (with data and assumptions): Populate tools with relevant data and assumptions in a transparent and traceable manner
4. **Test** (including regressions) & Sign off: Test whether the tool functions like it should and sign off on the use of the tool and its outputs
5. **Use**: Be clear how the model should be used, log errors, use version control.
6. **Review**: Review the tool against original specification. Refresh if necessary

It is essential to produce appropriate documentation at every stage of the development cycle and to establish stakeholder communication in accordance with their roles and responsibilities. In the context of AQUA, the following main stakeholder roles and responsibilities are defined:

1. **Commissioner**: Responsible for ensuring that those responsible for carrying out the analysis or developing the tools and models, do understand the context of the underlying questions and objectives so that they understand the likely risks and can determine what the appropriate analytical and quality assurance response should be. The commissioner also has a role to ensure that there is enough time and resource for the required level of assurance to be delivered and that they understand the associated risks when time and resource pressures are unavoidable. When using the analysis, the commissioner must understand the strengths, limitations, inherent uncertainty and the context of the analysis so that the results are interpreted correctly.
2. **Analyst**: Responsible for delivering the analysis or developing the tool. The analyst assists the commissioner in structuring the underlying questions and objectives to ensure the appropriate analysis is performed. Analysists should also provide proportionate documentation that outlines the

verification and validation activities undertaken and the associated conclusion. In addition, analysts should determine and communicate the uncertainty associated with the outputs of their analysis so that commissioners and end-users of tools, models and analyses results can make informed decisions.

3. **Analytical Assurer**: Responsible for providing evidence that appropriate analytical quality assurance activities have been conducted and that residual uncertainties and risks are understood and communicated (e.g. informing and advising the commissioner on quality assurance activities and any outstanding risks). Typically, this would be done by a senior analyst or analytical project manager who is not one of the analysts delivering the analysis. This activity takes place throughout the life cycle of the analysis from understanding the problem, through designing the analytical approach, conducting the analysis and relaying the outputs. The extent of quality assurance activities should be proportional to the risk and impacts addressed

6.3 Quality assurance & quality analysis

The main objective of the risk toolbox platform is to establish a national framework for development, maintenance, validation, dissemination and future support of (certified) tools used to assess and manage risks resulting from mining activities. To be able to complete this objective, proper quality assurance should be applied on the different tools in the risk toolbox, as well as for the risk toolbox itself. The criteria and aids for proper quality assurance are:

- **Documentation**: this is critical for allowing the transfer of knowledge. It should provide evidence of model requirements, accountabilities and risks
- **Structure & Clarity**: Tools should have a clear structure and provide information about labels, units, conversions, comments, formula clarity & robustness, etc.
- **Verification**: Is the tool working correctly? This includes formulas correctness, code correctness, regression testing, etc.
- **Validation**: Is the analysis appropriate for the purpose for which it is used? And in that respect, is the tool simulating reality as far as is possible? Ensure that the tool is a suitable representation of what is being analyzed, review of methodology, comparison with historical data/back-casting, sensitivity & scenario testing, etc.
- **Data and assumptions**: log and comment data and assumptions (e.g. data quality and statistical significance) used by tools within the toolbox throughout all development stages.

There is no single quality assurance approach. Quality assurance is delivered through a variety of different activities, each of which adds to the overall level of quality assurance. These should be evaluated through a quality analysis which addresses:

- Effective management of interactions between analyst and other stakeholders to ensure proportionality of QA efforts for the analytical project or tool.
- Confidence that the analytical output is fit-for-purpose
- Quantification and management of uncertainty and risks associated with the analysis and tools being evaluated

It is important that, at all stages of tool and toolbox development, a conscious decision on the amount and type of quality assurance is taken. When there are time or resource constraints, quality assurance activities should not be ignored. Instead, a risk-based approach should be used to highlight the areas of greatest potential error and focus on quality assurance efforts on these areas. It is also important that the impact of any reduction in the thoroughness of quality assurance activities is understood.

There is usually a trade-off between the available resources and time for the project and the level of QA activities that can be completed. With any analytical project, the competing aspects of the project need to be considered (Figure 6-2).

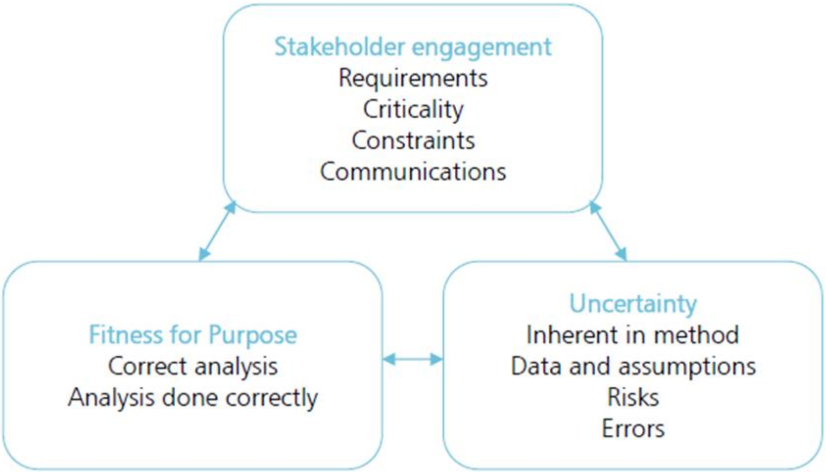

Figure 6-2: Trade-off between the available resources and time for a project and the amount of quality assurance that can be completed. Competing aspects of the project need to be considered. Source: The Aqua Book (2015)

The level of quality assurance for a tool within the Toolbox should depend on the risk associated with the intended use of the tool and on the complexity of the tool. A distinction can made here with respect to 1) verification of the functionality of the tool (e.g. being free of errors) and 2) validation of the results produced by the tool (e.g. are they fit for purpose and use in follow-up analyses).No single piece of guidance can provide a route to a definitive assessment of whether a piece of analysis is of sufficient quality for an intended purpose. The following principles of quality assurance will help delivery of *fit-for-purpose* quality assurance analysis:

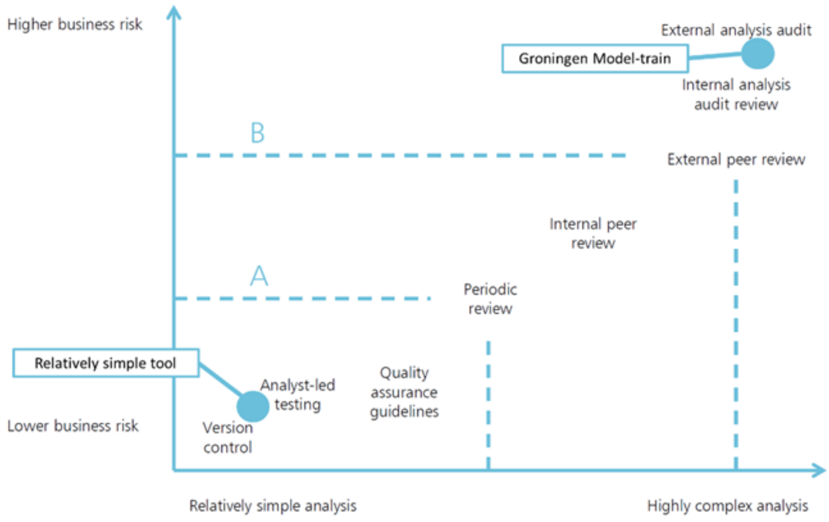

Figure 6-3: Types of quality assurance: Risk vs. complexity of analysis diagram. Source: The Aqua Book (2015)

6.3.1 *Proportionality of response*

The extent of the analytical QA effort should be proportionate in response to the risks associated with the intended use of the analysis (Figure 6-3). This means that the risk associated with a piece of analysis should influence the types of quality assurance activity that takes places. For example: the TNO Groningen model train scores high on *business risk* and high on *complexity of analysis* and will therefore need internal and external peer reviews for proper quality assurance. A simple tool with a relatively low business risk may only need Analyst-led testing for proper quality assurance (Figure 6-3).

6.3.2 *QA throughout development*

QA considerations should be accounted for throughout the life cycle of the analysis and not just at the end. This is also explained in the Model Cycle (Figure 6-1)

6.3.3 *Verification and Validation*

Analytical quality assurance involves both verification and validation aspects. Verification checks whether the analysis (tool) is error-free and satisfies its specifications. It can be thought of as checking that the model is solving equations correctly. Validation determines whether the analysis is appropriate for the purpose for which it is used? It can be thought of as checking that the correct equations are being used.

6.3.4 *Analysis with RIGOUR*

Quality Assurance needs to be repeatable, independent, grounded in reality, objective and well-understood. Uncertainty must be managed, and results should robustly address initial question. It is important to accept that uncertainty is inherent with the inputs and outputs of any piece of analysis. It is also important to establish how much can be relied on the analysis for a given problem.

The RIGOUR principle stands for:

- **Repeatable**: For an analytical process to be considered 'valid' it might reasonably be expected that for the "same" inputs and constraints the analysis produces the "same" outputs. It is important to note that different analysts will consider the analytical problem differently, potentially resulting in differing results, however if any one approach is repeated the results should be as expected.
- **Independent**: To produce analysis that is free of prejudice or bias. In doing so, care should be taken to appropriately balance the views across all stakeholders and experts.
- **Grounded in reality**: Quality analysis takes the commissioner and analyst on a journey as views and perceptions are challenged and connections are made between the analysis and its real consequences. Connecting with reality in this way guards against failing to properly grasp the context of the problem – which is being analyzed.
- **Objective**: Effective engagement and suitable challenge reduces potential bias and enables the commissioner and the analyst to be clear about the interpretation of the analytical results.
- **Uncertainty-managed**: Uncertainties have been identified, managed and communicated throughout the analytical process.
- **Robust**: Provide the analytical result in the context of residual uncertainty and limitations to ensure it is used appropriately.

6.4 Implementation

The details regarding implementation of the quality assurance procedures should be elaborated during a following toolbox specification and development phase. As a general guideline the following preparatory quality analysis steps are considered:

Determination of the level of quality assurance required for each tool. What is the complexity of the tool and what is the significance of the risks and impacts being addressed by the tool (see also Figure 6-3). This will lead to the definition of a fit-for-purpose quality assurance protocol for every separate tool.

Evaluate the existing quality assurance for each tool. Which elements are already in place (e.g. validation, documentation, etc.). Based on this evaluation, additional steps can be defined to achieve compliance with the above-mentioned requirements. These steps can be ranked according to the quality assurance criteria: Documentation, Structure & Clarity, Verification, Validation and Data & Assumptions.

It should be noted that a model train of linked tools requires a protocol that is often suited for a more complex quality assurance. The individual tools included in the train also exhibit a separate (simpler) quality assurance protocol.

6.5 Extensions to the Aqua Book

The Aqua quality assurance framework was initially made for high impact analyses and single models (tools), although also suitable for low impact analyses. A tool-chain has characteristics which are more complex: it combines multiple models into

chains which interact with each other. There can be a variety in production scenario's with different model chain settings. Due to the variability and complexity or scale of a model train there is a need for quality assurance automation.
The Aqua book assumes that when the final version of tool or tool-chain is delivered, the Model Cycle is completed. However, after the Design and Delivery phases there should also be a Support phase in which reactions and/or complaints about the results can be handled (Figure 6-4). When QA is important, reactions on the produced results can and must be expected. This is especially important in high complex, high impact tools like the TNO Groningen model train tool.

Within the scope of Aqua, the Design and Delivery quality assurance phase is covered. These phases contain analysis with RIGOUR (for quality assurance) and Testing (for Verification and Validation). For all tools a third quality assurance phase should be added which is the Support phase. This phase takes place after results are produced, or when the outcome of the final version of a tool is delivered and it's Aqua-Model Cycle is completed. It depends on the situation how much effort and automation are put into the support phase. That must be a conscious decision and not a regret when it is too late to collect and store all relevant information. Within the support phase the quality assurance should provide transparency and explainability of the delivered result. Which choices were made, and which models, and what data and configuration settings were used to create the result? To be able to do that all relevant information should automatically be collected within the Design and Delivery phase. Automation will ensure that, after the results are delivered, all foreseen questions about transparency, explainability and complaints can be answered using traceability for all versions of the tool, data and configuration and – if necessary – it is possible to provide automatic reproducibility of the result.

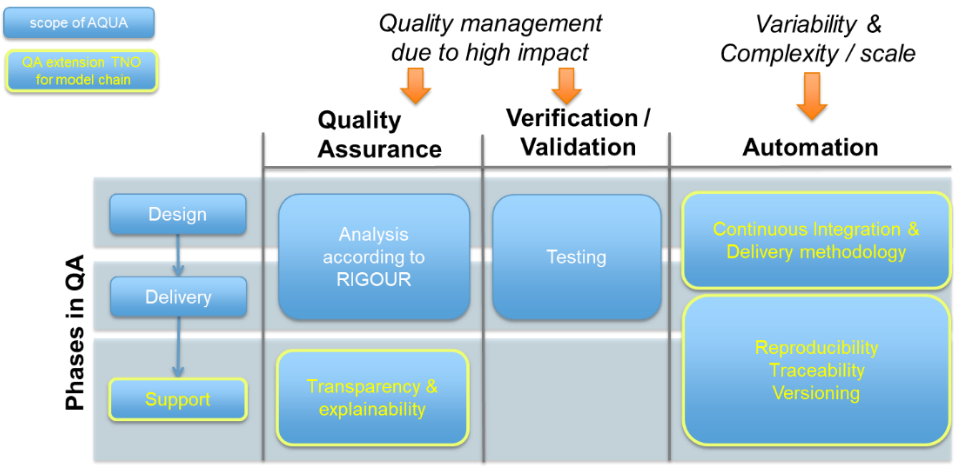

Figure 6-4: Quality assurance scope of Aqua with the addition of the TNO quality assurance extension for the Groningen model train tool. The Support phase is added to make sure that there is transparency and explainability after the tool is delivered. Automation should be added in all quality assurance phases to provide the proper quality assurance.

7 Strategic agenda for mining risk tools and research

7.1 Introduction

The main objectives for the strategic agenda are to:
- Identify knowledge gaps and tool limitations[21] hampering the effective assessment and management of mining risks.
- Recommend and prioritize actions towards resolving these knowledge gaps with improved risk tool functionalities

The strategic agenda is subdivided in two main components, i.e.:
- **Toolbox agenda**: A program for <u>development, maintenance, quality assurance and dissemination of tools</u> for risk assessment related to mining activities. The national research institutes (TNO, Deltares, KNMI) are asked to coordinate this new component through a national mining risk toolbox. The recommendations for development, maintenance and quality assurance are presented in chapters 5 and 6.

- **Research agenda**: A program for <u>fundamental research</u> on the causes, prevention and mitigation of mining risks. This component is currently accommodated in KEM and associated research programs (DeepNL, NCG). This strategic agenda formulates priorities for the above-mentioned research programs. The objective is also to secure and connect, maintain and deploy the outcome of research developed within KEM, DeepNL and NCG through the risk toolbox. The recommendations for research are provided in the following paragraph.

7.2 Strategic agenda: research recommendations

Table 7-1 summarizes the main outcomes of the state of play presented in Chapter 3. This table also includes a priority ranking to address shortcomings and new developments.

A high ranking in Table 7-1 is related to:
- the demand for knowledge and tools for actual high-risk levels and associated impacts
- the demand for knowledge and tools needed to prevent and manage risks and impacts that could evolve from planned (future) mining activities.

The different ranking classes are explained below:
1. **Urgent**: actual risk with potentially big impacts. Current knowledge and tool not fit for adequate risk assessment and risk management. Priority for the research and risk tool development programs within the next 5 years
2. **Important**: Risk level is uncertain and depends on development of mining activities or pending identification of actual risks. Need for knowledge and tools is contingent and could become a priority in the near future.
3. **Low priority**: knowledge, tools and protocols are adequate for the current situation

[21] Either lack of tool functionalities or deficiencies in tools performance

The ranking presented in this study, is based solely on technical criteria and follows from the inventories presented in Chapter 3 and 4, as well as the expert judgement of the project team. Alternative non-technical criteria (e.g. societal perception, economic impact) may lead to a different scoring.

Category		Risk level	Need for			Ranking
Mining activity	**Hazard**		**Know-ledge**	**Tools**	**Proto-cols**	
Oil and Gas	Seismicity	gro Oth	gro oth			1
	Surface deformation					2
	Leakage and migration					1
	Facility	off On		off on	off on	3
Geothermal	Seismicity	std Udg				1
	Surface deformation					n/a
	Leakage and migration					2
	Facility					3
Storage And Injection	Seismicity					2
	Surface deformation					3
	Leakage and migration		hyd ugs	oth ugs	oth ugs	1
	Facility	hyd Ugs	oth ugs		oth ugs	2
Salt Mining	Seismicity					2
	Surface deformation					1
	Leakage and migration					1
	Facility					3
Coal Mining	Seismicity					2
	Surface deformation					1
	Leakage and migration					2
	Facility					n/a

Table 7-1: Overview of state of play and ranking of urgent issues for the strategic agenda. Ranking explained in text.

The following sections provide an overview of research and tool development agenda actions which are recommended to be addressed within the next 5 years (i.e. technically ranked as urgent). The recommendations are grouped by hazard/risk category.

7.2.1 Seismicity

<table>
<tr><td colspan="2">Agenda topic: Oil/gas production – Seismicity</td></tr>
<tr><td colspan="2">Issue / concern: Groningen seismic risk assessment
Risk levels for the Groningen gas field remain high. There are uncertainties concerning the occurrence of high magnitude earthquakes and their impact.</td></tr>
<tr><td>Research recommendations:
• Increase knowledge concerning occurrence of (high magnitude) earthquakes, propagation of seismic waves in shallow subsurface, peak ground acceleration.</td><td>Tool recommendations:
• Update the model trains as new knowledge and data become available</td></tr>
<tr><td colspan="2">Expected impact:
Improved prediction of future (long term) seismicity and possible regions with increased risk</td></tr>
<tr><td colspan="2">Effort:
The Groningen research is already firmly embedded in the current KEM, NCG and EZK/SODM programs</td></tr>
</table>

<table>
<tr><td colspan="2">Agenda topic: Geothermal – Seismicity</td></tr>
<tr><td colspan="2">Issue / concern: Seismic monitoring network and hazard determination:
Currently there is a growing number of geothermal installations in regions where the coverage of KNMI’s seismic monitoring network is not suited for a detailed localization of earthquakes. Recent small earthquakes near geothermal installations are raising concerns for potential future seismicity and resulting impacts.

The risk level for geothermal (in particular ultra-deep) can become high with ongoing development of new projects. Knowledge, dedicated risk tools and mature protocols are currently either lacking or considered too immature for an adequate assessment of hazards and risks.</td></tr>
<tr><td>Research recommendations:
• Investigate approaches to better localize earthquake sources through improved seismic velocity models
• Improve knowledge on the potential causes, intensity and expected impacts of earthquakes generated by geothermal activities
• Establish an improved national knowledge base for analyzing and predicting fault behavior, especially for stressed faults.
• Improve knowledge on the subsurface in areas where gas production is not present to enhance the reliability of subsurface models.</td><td>Tool recommendations:
• Resolve sparse coverage of the seismic monitoring network in regions with existing and planned mining activities that are known to induce earthquakes. In particular geothermal sites, but possibly also storage and salt mining locations.
• Adapt the existing oil/gas seismic risk tools for use in geothermal seismic risk assessments
• Optionally: incorporate these tools in a composite model train (cf. the Groningen model train)
• Development of Ground Motion Models for mining activities outside Groningen</td></tr>
</table>

Expected impact: Detailed localization and moment tensor inversions of earthquakes and compiled knowledge on fault behavior will significantly improve the understanding of local causes and mechanisms for seismicity. Such knowledge is crucial for the identification of potentially stressed faults and providing better risk assessments of (newly planned) mining activities. Given the expected steep growth of geothermal activities, including ultra -deep), a composite model train dedicated to geothermal developments, is expected to increase the efficiency and effectivity of seismic risk assessments.
Effort: The densification of the monitoring network is an ongoing effort, best placed under a national program (KNMI). Research institutes and SodM should evaluate new regions for further network improvement on a yearly basis. The development of e.g. accurate P and S velocity models for regions where mining activities are ongoing or planned is crucial for the application of innovative high precision location methods. A seismic risk and hazard protocol is currently under development. The development of dedicated geothermal risk tools has priority and will probably take at least 2 years before reaching a validated status. The development of a geothermal seismic risk model train is expected to take several years before it can be fully deployed. It is recommended to place this development under a specific program under the risk toolbox. The foundations for a knowledge base are currently developed in European projects (TNO, KNMI). Information should be maintained and updated by the national geological research programs (GIP).

7.2.2 *Surface deformation*

Agenda topic: Salt mining – Surface deformation	
Issue / concern: Long term subsidence effects, salt caverns Many salt caverns will be abandoned in the near future. There is adequate knowledge and track record regarding the long-term effects and impacts of cavern convergence.	
Research recommendations: • Build a data and knowledge base for the prediction of long-term convergence and subsidence effects due to abandoned salt caverns.	**Tool recommendations:** • Establish monitoring programs for old/abandoned salt caverns • Update the current subsidence tool sets for improved modeling and prediction of convergence and subsidence after closure and abandonment. • Establish abandonment protocols for finished and unused caverns.
Expected impact: Improved prediction of risk from future (long term) subsidence effects above abandoned salt caverns. Adaptation of abandonment plans to reduce or mitigate subsidence effects.	

Effort: The deployment of monitoring networks and building of a validated knowledge base will take several years. It is recommended to place these activities under a dedicated monitoring and measurement program, linked to the national research institutes.

<table>
<tr><td colspan="2">Agenda topic: Coal mining – Surface deformation</td></tr>
<tr><td colspan="2">Issue / concern: Rising mine water Limburg
In southern Limburg a gradual rise of surface level and ground water level occurs as a result of rising mine water levels (swelling of the soil and pressure build-up in subsurface mine workings). Additionally, abrupt subsidence and collapse can take place at older (poorly abandoned) or shallow (<100m) mine workings which have been developed before 1960. Effects are expected to continue over the next 20-40 years.</td></tr>
<tr><td>Research recommendations:
• Build a data and knowledge base for the prediction of long-term convergence and subsidence effects in abandoned mine workings.
• better understanding of irregular surface movement (due to rising mine water).</td><td>Tool recommendations:
• There is a need for improved monitoring capabilities for abandoned coal mines and solutions for stabilizing old mines at risk. Accurate risk contours should be established for abandoned mine workings. Furthermore, an Early Warning System for surface movements is recommended. A basis for such warning and risk management system is elaborated in GS-ZL 2016 and Roest et al. 2018[22].</td></tr>
<tr><td colspan="2">Expected impact:
Effective protocol based on improved monitoring and management of risks with an Early Warning System and a better insight in risk development resulting from rising mine water and associated uplift effects in the former Limburg mining district.</td></tr>
<tr><td colspan="2">Effort:
The deployment of monitoring networks and building of a validated knowledge base will take several years. It is recommended to place these activities under a dedicated monitoring and measurement program, linked to the national research institutes.</td></tr>
</table>

[22] Roest, Kragten, Witteveen&Bos, 2018. Risicosignalering na-ijlende effecten steenkoolwinning. GS-ZL, 2016. Na-ijlende gevolgen steenkoolwinning

7.2.3 Leakage and migration

<table>
<tr><td colspan="2">Agenda topic: Oil/gas – Leakage and migration</td></tr>
<tr><td colspan="2">Issue / concern: Methane and other content leakage from legacy and abandoned well.
Any well during its operational lifetime can be affected by leakage, however active monitoring during production will give immediate notice of any structural failure of a well (well casing/cement integrity). Such monitoring is not clear and present for legacy and abandoned wells. Monitoring campaigns have started to produce a comprehensive insight in possible (methane) leakages from abandoned and legacy oil and gas wells. The objective is to predict future risk levels (e.g. impact on groundwater quality) and to develop adequate remediation measures. It is recommended to incorporate the results in an assemblage of risk tools which are focused on managing and reducing long term impacts from abandoned wells related to all types of mining activities (including, oil and gas, geothermal and subsurface storage).</td></tr>
<tr><td>Research recommendations:
• Material attributes of well casing/cement and other materials used to closedown abandoned wells
• Further inventory and monitoring of leakage at wells
• Determine local and regional sensitivity to migration of pollution.</td><td>Tool recommendations:
• Well assessment tool, showing life time and integrity of the design.
• Aquifer Risk assessment tool, showing local and regional sensitivity to leakage and migration potential.
• Guidelines for managing these risks and protocols for abandonment.
• Currently the investigation of leakage and migration of mining-related contaminants is dispersed over many different individual tools. It is therefore recommended to integrate these tools in composite model trains to enable a more effective and better structured assessment of leakage hazards.</td></tr>
<tr><td colspan="2">Expected impact:
Improved management of risks and subsequent mitigation with an assessment tool and guideline for designing the well for abandonment.</td></tr>
<tr><td colspan="2">Effort:
A provisional tool to assess leakage and migration potential could be developed with limited effort.

Testing and assessing of materials and how they actual behave under the specific conditions in the subsurface being in contact material collected in the wells over time, for prolonged periods will take considerable effort.

It is further recommended to investigate the possibilities of a seamless integration with the currently existing risk toolboxes for soil and groundwater, which would add the functionalities necessary to assess concrete impacts and risks to humans and ecology. For instance, tools showing the sensitivity of the (fresh) groundwater system for the near surface could be developed using available models such REGIS-II.</td></tr>
</table>

<table>
<tr><th colspan="2">Agenda topic: Salt mining – Leakage and migration</th></tr>
<tr><td colspan="2">Issue / concern: Permeation of brine and diesel from abandoned caverns
Use of subsurface salt caverns have been studied for many applications, ranging for compressed air, hydrogen gas to strategic reserves for diesel. Current practice is that after production, during abandonment caverns are filled with brine and capped with gas-oil to prevent collapse. Practical applications have shown that leakage is a relevant concern.

It is recommended to directly investigate essential tool functionalities and consolidate the risk management of storage activities within salt caverns. In line with these functionalities various research questions need to be addressed including the influence of stored fluids/gases on reservoir, seal integrity and wells

These questions are also relevant for future applications such as hydrogen and CO_2 storage. Actual preparations for CO_2 storage in the offshore P/Q blocks oblige the establishment of mandatory injection plans, risk management plans, monitoring plans and abandonment plans (specifications starting in 2019).</td></tr>
<tr><td>Research recommendations:
• The influence and effect of stored fluids/gases on the cavern walls, reservoir matrix, reservoir boundaries, seal integrity and well casing/cement integrity, the integrity of pipelines used for transport.
• Inventory of leakage and migration of stored fluids/gases
• Monitoring of reservoirs used to store fluids/gases
• Determine local and regional sensitivity to migration of pollution.</td><td>Tool recommendations:
• Cavern/reservoir assessment tool, showing life time and integrity of the design for storage of fluids and gases.
• Aquifer Risk assessment tool, showing local and regional sensitivity to leakage and migration potential.
• Guidelines for managing these risks and protocols for storage.
• Currently the investigation of leakage and migration of stored contaminants is dispersed over many different individual tools. It is therefore recommended to integrate these tools in composite model trains to enable a more effective and better structured assessment of leakage hazards.</td></tr>
<tr><td colspan="2">Expected impact:
Improved management of risks and subsequent mitigation with an assessment tool and guideline for designing the use of caverns and reservoir for the storage of fluids and gases.</td></tr>
<tr><td colspan="2">Effort:
A provisional tool to assess leakage and migration potential could be developed with limited effort. However, testing and assessing of materials and how they actual behave under the specific conditions in the subsurface being in contact stored fluids and gases, for prolonged periods will take considerable effort.

It is further recommended to investigate the possibilities of a seamless integration with the currently existing risk toolboxes for soil and groundwater, which would add the functionalities necessary to assess concrete impacts and risks to humans and ecology. For instance, tools showing the sensitivity of the (fresh) groundwater system for the near surface could be developed using available models such REGIS-II.</td></tr>
</table>

7.3 Strategic agenda: general recommendations

The following sections summarize the more generic recommendations with regards to the linkage of the development agenda of risk toolbox (chapters 5 and 6) and the strategic research agenda presented in Paragraph 7.2.

7.3.1 Consult other stakeholders for alternative definitions of ranking of priorities

It is recommended to investigate further extension and broadening of the priority ranking, eventually based on other, non-technical criteria such as societal perception, economic impacts, etc. It is recommended to query, communicate and approve these criteria based on the input of a broader stakeholder group.

7.3.2 Establish a framework for regular strategic agenda updates, which allows for ad-hoc actions.

It is recommended to follow the current scheme of evaluation and updating of the KEM program. The evaluation of the toolbox agenda should be included in this cycle as well. During the program evaluations, the embedding of KEM research results in the risk tools and the associated funding should be a standard item on the agenda. As part of this evaluation, the KEM program and toolbox evaluations are recommended to provide an update of the state of play as presented in Chapter 3.

It is recommended to implement procedures that will allow for a timely identification and handling of ad-hoc and urgent issues related to assessment of mining effects and risks. These could include bug fixes or adaptations of tools responding to actual developments in mining activities.

7.3.3 Agree on clear and objective criteria to rank the priority of strategic agenda actions

Objective criteria are essential for a transparent definition and prioritization of actions under the strategic agenda. These criteria should be agreed between the responsible institutes, the accountable bodies and key stakeholders. Within this study the ranking is determined on the following criteria:

- The current risk level and scale/extent of impacts
- The evolution of risks resulting from future developments (e.g. new mining activities, abandonment schemes)
- The current effectiveness of existing tools and measures to prevent/mitigate/manage the risks
- The expected longevity and recurrence of risks (e.g. incidental or structural)

Based on the outcomes of this study, it is recommended to discuss and formalize the criteria between all relevant parties involved.

7.3.4 Define a regular and flexible budget/funding for the risk toolbox based on the priorities defined in the strategic research agenda

The risk toolbox incorporates regular risk-tool and toolbox maintenance activities (e.g.: quality assurance procedures, storing and disseminating tools, evaluating need for new functionalities, platform maintenance) as well as yearly programmed activities related to implementation of new tool functionalities (KEM, DeepNL and NCG program results).

It is recommended to assign a standard budget for regular tool maintenance. In the first two years, this budget is higher due to the start-up and development costs for the risk toolbox platform and the uptake of tools.

8 Governance Framework

8.1 Introduction

The development, maintenance and deployment of risk tools involves a complex interaction of different activities and responsibilities that are allocated to a broad community of commissioners, tool developers and end-users. These may include policy makers, administrators, inspectors but also entrepreneurs and consultants. Furthermore, the risk toolbox will be closely linked to national research programs (both in defining new research topics and embedding the outcomes). A governance framework essentially identifies responsibilities and accountabilities with regards to the definition of the strategic agenda on mining effects research and the implementation of the national toolbox for mining risk tools.

Basis for designing a governance structure for the risk toolbox and strategic research agenda is contained in the UK recommendation for Quality Assurance of Government business critical analytical/assessment models:

- All models (in the toolbox) need QC on inputs, methodology, and outputs
- For each model (in the toolbox) there should be a single Senior Responsible owner (model SRO) through its lifecycle
- All models need be managed in a (toolbox) framework (program) ensuring specialist staff are responsible for developing, releasing and using the models
- An Accounting Officer governance statement should ensure and confirm that appropriate Quality Assurance is in place for all models (in the toolbox)
- All executing organizations at arm’s length should have a yearly plan for work and the right QA environment and culture
- The process and its outcomes are subject to regular (international) external expert reviews

In the Netherlands there are various examples where a risk toolbox has been developed by co-creation between government (accountable) and research institutes (responsible). These include among others:

- Transport system (and sound) risk models (TNO),
- Climate risk and weather forecasting models (KNMI), Flood & drought risk models and early warning systems (Deltares)
- Emission risk models (TNO) and air quality warning system (KNMI)

The following sections will further focus on 1) defining the roles and responsibilities 2) identifying ownership, accountability and decision rights, and 3) establishing a clear structure for communication, interaction and transparency between all parties involved. These aspects are covered in the following sections.

8.2 Framework for roles and responsibilities

This paragraph presents the key recommendations for setting up a governance structure for the strategic agenda and the maintenance of the risk toolbox. It is proposed to define the governance structure and roles/tasks according to the RACI model.

The RACI model is an established and commonly used tool for identifying roles and responsibilities and avoiding confusion over those roles and responsibilities in a project or process[23]. The acronym RACI stands for:

Responsible: The person who does the work to achieve the task. They have responsibility for getting the work done or decision made. As a rule, this is one person; examples might be a business analyst, application developer or technical architect.

Accountable: The person who is accountable for the correct and thorough completion of the task. This must be one person and is often the project executive or project sponsor. This is the role that responsible is accountable to and approves their work.

Consulted: The people who provide information for the project and with whom there is two-way communication. This is usually several people, often subject matter experts.

Informed: The people kept informed of progress and with whom there is one-way communication. These are people that are affected by the outcome of the tasks, so need to be kept up-to-date.

The main responsibilities considered in the context of this report are:

- The definition and proposed priority ranking of research agenda topics
- The development and maintenance of the risk toolbox and coordination of the quality assurance procedures

8.3 Proposed implementation of roles and responsibilities

The key governance aspects in relation to this report are:

- The definition and prioritization of the strategic research agenda
- The development, deployment and maintenance of the risk toolbox

The risk toolbox will provide a framework for the KEM, DeepNL and NCG programs in which research results can be realized into practical tools and protocols for risk assessment. The effectivity of the risk toolbox will strongly depend on a proper alignment of the research agenda and risk toolbox through a close linkage of both governance structures.

Service Level Agreements (SLAs) are proposed to ensure quality & availability of models and tools. These SLAs can be defined at different levels and assigned to specific actors. A conceptual example is given below for the Seismic Hazard and Risk Assessment (HRA):

Level 1: SLA for definition of seismic HRA information services at higher policy level (scenario evaluation results, short term predictions). Accountability: MEA and/or SodM
Level 2: SLA for ensuring availability of seismic HRA model capacity (1. policy model train, 2. early warning facility). Accountability: MEA/SodM, Responsibility: TNO, KNMI, etc.

[23] www.projectsmart.co.uk

Level 3: SLA for the development of seismic HRA software tools (model train modules and models, stochastic simulation software). Accountability/responsibility: TNO, KNMI, etc.

Level 4: SLA for maintenance and access of seismic HRA databases (seismometer data, seismic events, reservoir/fault model, velocity model, building database, etc.). Accountability/Responsibility: respective owners of these databases, e.g. TNO, KNMI, Operators, etc.

To implement the above-mentioned governance framework, the following questions should be answered:

- What level of SLA is wanted/needed
  - Separate data, software, model or integrated?
  - What use is expected, what is the user group?
- Accountability:
  - Who is responsible EZK/SodM?
  - Which person is AO and what yearly budget is needed?
  - Which persons are SRO’s (steer content)?
  - What is the decision process workflow, criteria?
  - How is QC organized (KEM panel?)
- Responsibility
  - Who is responsible for the Toolbox program?
  - What are the products?
  - Which persons are product manager and principal investigators?
  - How is QC organized (internal/external reviews)?

8.3.1 Proposal for the strategic research agenda governance

- <u>Responsibility (definition of the strategic research agenda):</u>
  It is recommended to establish a commission of the key national institutes who are responsible for the definition and ranking of essential research topics related to mining hazards and risks in the Netherlands. This commission is proposed to be coordinated by TNO, KNMI and Deltares. These institutes already have a long track record with regards to the assessment of mining risks, the development and application of risk tools and the maintenance of national subsurface models and data repositories.

- <u>Accountability (Confirmation and approval of the strategic research agenda):</u>
  SodM and MEA are accountable for the KEM program. Associated research programs are led by various other organizations (e.g. DeepNL by NWO, NCG by the National Coordinator Groningen). These accountable organizations will decide on the publishing and funding of research topics proposed by the responsible commission. To effectively address the prioritized research questions, it is vital to establish to run these programs in good communication with each other.

- <u>Consultation:</u>

The commission responsible for establishing the research agenda, will consult various stakeholders and institutes who are involved in mining risk assessment, management and advise (e.g. operators, regulators, consultants). SodM and MEA (as accountable organizations) will consult the international KEM panel to support their decisions with regards to the strategic agenda.

- Information:
  All stakeholders, the scientific community and the public in general, are informed via the established portals of the various research programs. It is recommended to use the risk toolbox platform as a central portal through which all research programs can be accessed.

  In the report "Aardbevingsrisico's in Groningen" the Dutch Safety Board (OvV) recommends to implementing a more integrated approach and research framework on mining effects research. Fundamental research and knowledge institutes are crucial entities within this framework to jointly define the required levels of content and governance for a national research agenda. Establishing adequate communication between decision bodies and the supporting organizations is an essential first step in this process.

8.3.2 Proposal for the risk toolbox governance

- Responsibility:
  The main responsibility for the development and maintenance of the risk toolbox is proposed to be allocated at TNO. Deltares and KNMI should then be involved as consortium partners. A similar structure is used for the development of the Groningen model train. This responsibility covers among others the development and deployment of the risk toolbox platform (including its core functionalities such as the administration and dissemination of risk tool data), the implementation of the quality assurance procedures and the coordination of new functionality updates following from the research programs.

- Accountability
  SodM and/or MEA are accountable for the development and maintenance of the risk toolbox. This includes among others the approval of proposed and tool platform developments, criteria for quality assurance procedures, deployment of tools, etc. as well as decisions with regards to the funding of development and maintenance activities

- Consultation
  The risk toolbox consortium will consult all institutes who are responsible for the development and dissemination of relevant risk tools. The consultation may concern a variety of topics including the demand for tool upgrades, new toolbox functionalities, evaluation of the QA procedures, accessibility and deployment of tools, etc.

- Information
  All stakeholders, the scientific community and the public in general, are informed via workshop sessions, newsletters and further information published via the risk toolbox platform.

8.4 Communication and interaction

Communication and interaction structures should be established and agreed upon by the institutions responsible and accountable for the research agenda and toolbox development and maintenance. The KEM panel and other stakeholders (e.g. representatives from other major institutes such as RIVM, KWR and various universities, end-users, principal developers) should be consulted to review and support the approval of the strategic research and tool development agendas as well as for reviewing the research and tool development outcomes. Examples of interactions considered are:

- Alignment of the research activities under the strategic research agendas and the development of tools (e.g. embedding research results in mining risk tools and proposing research topics based on lacking tool functionalities)
- Alignment of quality assurance procedures and the start-up of new tool developments
- Decision, approval and review of research and tool development activities (e.g. KEM panel)
- Consultation of stakeholders and end-users with regards to the ranking of research priorities and the development of toolbox and platform functionalities.
- Setting up communication structures with end-user communities (e.g. discuss platform requirements, information, dissemination) and developer communities (e.g. discuss tool development, quality assurance procedures

9 Signature

Utrecht, 25 juli 2019 TNO

Drs. J.A.J. Zegwaard
Head of Advisory Group of Economic Affairs

Serge van Gessel [TNO]
Karin van Thienen-Visser [TNO]*
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Annex A: Risk tools

The table below lists the tools that have been regarded in the study. The list is not fully comprehensive and more tools will be added and considered for the risk toolbox

Mining Hazard/risk	gas/oil	geothermal	storage	salt	coal	general	Name of tool	Short description tool	Owner / developer
0. Risk management			x				SAMCART	Risk analysis database with quantitative measures based on a series of process studies	TNO
0. Risk management						x	DAPP	The Dynamic Adaptive Policy Pathways (DAPP) approach aims to support the development of an adaptive plan that is able to deal with conditions of deep uncertainties.	Deltares
0. Risk management						x	DINO deep database	Database of deep subsurface data (public and confidential)	TNO
0. Risk management						x	Kosten baten analyse Subsidence	Measurement strategy tool	Deltares
1. Seismicity	x	x	x				Water injection protocol		SodM
1. Seismicity	x	x		x			Accelerometers	monitoring	KNMI
1. Seismicity	x	x		x			KNMI dataportal	data portal for seismic data	KNMI, GFZ
1. Seismicity	x	x		x			Obspy	program for analysis of Seismicity	Muenchen univ.
1. Seismicity	x	x		x			Pyrocko	Moment tensor inversion	GFZ
1. Seismicity	x	x		x			Seiscomp3	program for real-time Seismicity monitoring	GFZ/Gempa + KNMI
1. Seismicity	x	x		x			seismometers	monitoring	KNMI
1. Seismicity	x	x					deepsoil	calculation of site response, shallow subsurface response of earthquakes (non-linear)	Deltares, extension to university of illinois
1. Seismicity	x	x					Hydraulic stimulation protocol		SodM
1. Seismicity	x			x			RRSM interface	PGA, PGV measurements+waveforms	KNMI, ODC, ETH
1. Seismicity	x			x			Shakemap	PGA, PGV map for earthquakes M>2.0 (Groningen)	USGS, KNMI
1. Seismicity	x						Abaqus FEA	Abaqus FEA numerical model for SSI behaviour	Dassault Systèmes
1. Seismicity	x						Abaqus FEA for structural calculations	Abaqus FEA numerical model for structural behaviour	Dassault Systèmes
1. Seismicity	x						Bayesian Change Point Model	Matlab script for determining statistically significant change in seismicity	Stanford University
1. Seismicity	x						Cyclic hysteretic soil model (Abaqus	Cyclic hysteretic soil model in Abaqus FEA	Dassault Systèmes

Mining Hazard/risk	Name of tool							Short description tool	Owner / developer
	gas/oil	geothermal	storage	salt	coal	general			
							FEA)		
1. Seismicity	x						DEEPSOIL	Site response simulation files	University of Illinois and Youssef Hashash
1. Seismicity	x						DHAIS	Script for calculating boundary values of DHAIS (E, B, dP/dPini)	TNO
1. Seismicity	x						Groningen Modeltrain	Framework for seismicity to personal risk modelchain	TNO
1. Seismicity	x						Groningen Modeltrain	Framework for seismicity to personal risk modelchain	NAM
1. Seismicity	x						Groningen statistische analyse	statistische analyses aan het Groningenveld naar vorming van hotspots in het veld, bepaling escalatie of de-escalatie, trendanalyses	CBS
1. Seismicity	x						Matlab scripts: fragility function	Matlab scripts to evaluate the fragility function of structures	TNO
1. Seismicity	x						NAM Fragility function coefficients	v5 Fragility functions of all typologies	NAM
1. Seismicity	x						NPR Spectra Excel Sheet	CSV with UHS data	NEN
1. Seismicity	x						Opensees scripts: simulation of SDOF models	Opensees scripts for the simulation of SDOF models	TNO
1. Seismicity	x						Pipe quake	program for dynamics calculation of pipelines	Deltares + Uo Illinois
1. Seismicity	x						Plaxis	program for soil construction interaction	Plaxis bv
1. Seismicity	x						PLE4win	program for stability calculations pipelines	R+K
1. Seismicity	x						Python script: Response Spectra (ISO)	Script in Python for Response Spectra according to ISO	TNO
1. Seismicity	x						Python script: soil springs and dampers	Script in Python for determination of soil springs and dampers	TNO
1. Seismicity	x						Reasenberg algorithm	Matlab script for removal of aftershocks in catalogue based on Reasenberg	adopted from Reasenberg
1. Seismicity	x						Risk protocol for small gas and oil fields	Protocol for assessement of seismic hazard and risk in small oil/gas fields	SodM
1. Seismicity	x						Seismic Hazard/Risk Asssessment	Script for calculation of boundary values in DHAIS (E, B, dP/dPini)	TNO
1. Seismicity	x						Seismische risico analyse voor winningsplannen	Script for determination of SRA scores	TNO
1. Seismicity	x						Small fields Petrel	3D Petrel model of each onshore oil/gas fields in	TNO

Mining Hazard/risk	**Name of tool**							**Short description tool**	**Owner / developer**
	gas/oil	**geothermal**	**storage**	**salt**	**coal**	**general**			
							models	NL (2016)	
1. Seismicity	x						STRATA	Site response simulation files	UoTexas, Albert Kottke
1. Seismicity		x					GeoMech V2	Excel spreadsheet for determining ratio of applied injection pressure with various pressure and stress gradients	TNO
1. Seismicity						x	BlockSpring	Fast analysis tool for rupture mechanics and flow throughout fractures	TNO
1. Seismicity						x	Diana	Software for basic/advanced analysis of a wide range of subsurface faulted structures	DIANA FEA BV
1. Seismicity						x	Earthquake statistics		TNO
1. Seismicity						x	Flac	Software for advanced geotechnical analysis of soil, rock, groundwater, and ground support in two dimensions	Itasca
1. Seismicity						x	MACRIS	Mechanical Analysis of Complex Reservoirs for Induced Seismicity. 3D mesh free stress oplossing, probabilistisc seismic hazard assesment	TNO
1. Seismicity						x	Neural network event detection	Passive seismicity: neural network event detection/location	TNO
1. Seismicity						x	Probabilistic Seismic Hazard Analysis		TNO
1. Seismicity						x	Probabilistic Seismic Risk Analysis		TNO
1. Seismicity						x	Seismic Event Characterization	Passive seismicity: deterministic event detection/location	TNO
1. Seismicity						x	SPASS	Software Package for Analysis of Stress and Stability	TNO
1. Seismicity						x	SpecFEM Seismic Modeling	State-of-the-art seismic wavefield modeling	Princeton, CNRS, UniMarseille, ETH
1. Seismicity						x	strata	Site response calculation seismic site response (equivalent lineair, and other)	Deltares + UoTexas
1. Seismicity						x	Telt	Analytical, radial-symmetrical thermo-elastic stress model	TNO
2. Subsidence	x			x			Knothe	Matlab script to calculate subsidence using the Knothe influence function and compare the results with method using influence function based on Van Opstal (1974)	TNO
2. Subsidence	x			x			Van Opstal (1974) routine	Van Opstal (1974) routine, calculates Greens function necessary to translate reservoir compaction to subsidence	TNO
2. Subsidence	x						Aesubs	programma wat Subsidence berekend door gas production	TNO

Mining Hazard/risk	Name of tool							Short description tool	Owner / developer
	gas/oil	geothermal	storage	salt	coal	general			
2. Subsidence	x						DEPOMET	Subsidence to compactie inversion based on Kalman filter	TNO
2. Subsidence	x						Redflag	Redflag matlab script (Red flag method is a tool to discriminate between models)	TNO
2. Subsidence	x						RTiCM (matlab)	Rate type compaction isotach formulation	TNO
2. Subsidence	x						Satellite measurements	Subsidence prediction based on satellite data	Deltares
2. Subsidence	x						Subsidencestool (Matlab)	Matlab scripts that first calculates reservoir compaction (linear, rate type, time decay) per gas field and consequently te corresponding subsidence using Van Opstal (1974) influence function).	TNO
2. Subsidence		x					DoubletCalc 2D	flow simulator, calculation of pressure depletion in reservoir and subsidence due to reservoir cooling	TNO
2. Subsidence		x					DoubletCalc 3D	flow simulator, calculation of pressure depletion in reservoir and subsidence due to reservoir cooling	TNO
2. Subsidence						x	Atlantis	Atlantis is an ecosystem box-model intended for use in management strategy evaluation	Deltares
2. Subsidence						x	D-settlement	D-Settlement comprises multiple methods for accurate modelling of consolidation, creep, construction phases en loading/unloading	Deltares
2. Subsidence						x	ESIP	Ensemble-based Subsidence Interpretation and Prediction	TNO
2. Subsidence						x	Extensometers	measurement tool to monitor vertical displacements	multiple
2. Subsidence						x	Gravity modeling and inversion	Gravity modeling and inversion	TNO
2. Subsidence						x	INSAR subsidence computation	INSAR subsidence computation	TNO
2. Subsidence						x	Laser	measurement tool to monitor elevations	multiple
2. Subsidence						x	Subcreep	Fluid flow-Subsidencesmodule in iMOD	Deltares/USGS
2. Subsidence						x	Subwt	Subsidence module in iMOD	USGS
3. Leakage	x	x			x		iMOD	programme for groundwater flow shell around Modflow)	Deltares
3. Leakage	x	x					Mfrac	Software for advanced analysis of a wide range of stimulation and petroleum engineering applications, including hydraulic fracturing and minifrac analysis	Baker Hughes
3. Leakage	x		x	x			STOMP	programme for multi-phase fluid flow in permeable media	PNNL
3. Leakage	x						Excel: Formation water salinity	Calculation of water properties using chemical composition	TNO

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3. Leakage	x						Excel: permeability uncertainty	Calculation of uncertainty in reservoir permeability in a well.	TNO
3. Leakage	x						Poro-perm relaties (excel)	Definition of van poro-perm relations using plugdata of the DINO database.	TNO
3. Leakage		x		x			Data: density fluid flow	data on over density fluid flow and salinity/thermal data	Deltares
3. Leakage		x		x			Modpath	programme for stroomlines and ages in groundwater	USGS
3. Leakage		x		x			MT3D	programme for thermic and reactive transport in groundwater	USGS
3. Leakage		x		x			SEAWAT	programme voor density flow by saline-fresh water differences	USGS
3. Leakage		x					Doublet Calc v1.4.3	program for calculating the indicative power of a geothermal doublet	TNO
3. Leakage		x					Excel: French circles	Excel sheet for defining the influence circles of a geothermal doublet	TNO
3. Leakage		x					Excel: production analysis	Analysis of monthly production data of operators (deels confidentieel) and derivation of parameters.	TNO
3. Leakage		x					Excel: Skin-Permeability	Calculation of skin and permeability using monthly production data	TNO
3. Leakage		x					French circle method	method to determine the area of influence of a geothermal doublet	-
3. Leakage		x					Glas fiber measurements	monitorings and proocessing tool for temperature measurements	Deltares
3. Leakage		x					Thermal fraccing tool	1d (radial symetrical) model for modelling the influence of temperature on a stress field	TNO
3. Leakage		x					Wellbore measurements	monitorings and processing tool to determine various wellbore parameters	Deltares
3. Leakage			x				CASSIF-FEP	Database on features, events and processess for CArbon Sequestration Scenario Identification Framework	TNO
3. Leakage			x				Data: geochemical reactivity	data on geochemical reactivity/labfacilities	Deltares
3. Leakage			x				Data: microbiological reactivity	data on microbiological reactivity/labfacilities	Deltares
3. Leakage			x				Mirecol Web App	Tool to assist the mitigation and remediation of carbon dioxide leakages in subsurface storage sites.	TNO
3. Leakage			x				Phreeqc	programme for reactive transport in groundwater	USGS
3. Leakage			x				PHT3D	programme for reactive multicomponent transport	CSIRO Land and Water Australia
3. Leakage						x	CGG Hampson Russell Strata	Active seismic: general data analysis/interpretation: Relevant for monitoring and data processing for processes in near	CGG

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								wellbore regions.	
3. Leakage						x	Coupled Modelling Tough-Flac3D	Software for advanced analysis of THMC coupled processes in subsurface faulted structures	University Aberdeen-PennState
3. Leakage						x	EM modelling and inversion	EM modeling and inversion	TNO
3. Leakage						x	Flexpde	coupling of thermal energy and groundwater fluid flow	Deltares
3. Leakage						x	PFC	Multi-physics simulation software based on Distinct Element Method (DEM) for analysis of e.g. mining, geotechnical, earth sciences processes	Itasca
3. Leakage						x	wanda	programme voor hydraulic design and simulation of of pipeline systems	Deltares
4. Facilities	x	x	x	x			MIC sensors	sensoren and processing for microbial corrosion	Deltares
4. Facilities						x	HUGIN-expert	Bayesian network software. Applied in AGS to discover insight and provision of predictive capabilities for risk of wells	HUGIN EXPERT A/S
4. Facilities						x	SEALEC (Diana)	Software for wellbore stability and integrity	DIANA FEA BV