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Report on risk analysis, best practices and lessons learned from existing geothermal projects in Germany

COSMA-1, D 1.2

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Geological **CO_2** **S**torage and Other E**m**erging Subsurface **A**ctivities
- Protection of Groundwater Resources, Phase 1 -

COSMA-1, D 1.2:

Report on risk analysis, best practices and lessons learned from existing geothermal projects in Germany

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1 Introduction

Increasing subsurface activities like geothermal energy production, unconventional gas exploitation (EGR – enhanced gas recovery), enhanced oil recovery (EOR) or geological carbon dioxide storage (GCS) are potentially hazardous for the environment. Especially fresh water aquifers used as drinking water resources need to be protected.

The first phase of the project COSMA focuses on potential hazards and hazardous events arising from those activities and aims at developing an approach for quantifying and comparing potential risks. A general description of hazards and hazardous events resulting from emerging subsurface activities is given in the first deliverable D1.1 "Geological CO_2 Storage and Other Emerging Subsurface Activities: Catalogue of Potential Impacts on Drinking Water Production".

In this 2nd deliverable, reported hazards and hazardous events resulting from geothermal energy production in Germany are described. This report includes analyses of enquiries to experts from all federal states, State Geological Surveys, information from standardization committees, developers, planners, drilling contractors, expert committees, consulting engineers and regulatory authorities such as environmental agencies, water authorities and mining authorities as well as from media reports.

It aims to list and categorize observed impacts arising from recent geothermal projects, as there have been increasing activities in this field in the past 10 years in Germany and because there are many similarities to other subsurface activities with respect to drilling processes, fracking methods and reinjection of fluids.

The German classification of geothermal systems distinguishes between shallow or near-surface (< 400 m depth) and deep geothermal energy (> 400 m depth) systems, which will be used in the following chapters. Table 1 shows the difference to international classification schemes, regarding enthalpies and temperatures.

Tab. 1: Classification of geothermal systems in France, USA and Germany with respect to enthalpies, temperatures and depth. Comparison of national and international classifications (after Massat, 2012).

Enthalpy		**Temperature**		**Depth**		
France	**USA**	**France / USA**	**Germany**	**France**	**Germany**	
very low enthalpy	low enthalpy	< 30°C	< 25°C	< 1000 m	< 400 m	near-surface (shallow) geothermal energy
low enthalpy		~ 30°C - 90°C	> 25°C	< 2000 m	> 400 m	deep geothermal energy
medium enthalpy	medium enthalpy	90°C - 150°C		< 4000 m		
high enthalpy	high enthalpy	> 150°C		> 4000 m		

The reported case studies of failures potentially leading to contamination of freshwater aquifers are described in chapter 2 with respect to the setting and the reason for failure (if known). Chapter 3 gives some recommendations with respect to possible precautions and countermeasures to prevent such potentially hazardous events.

Regardless of the drilling depth there are general hazards and hazardous events that must be taken into account for all subsurface activities. Amongst these are hazardous events during operation which can lead to a contamination of the site, hazardous events during drilling caused by wrongly selected drilling techniques, drilling into unknown caverns, cavities or caves or faulty casing, construction or plugging (sealing). Furthermore, unexpected chemical reactions between fluids and casing or sealing material (e.g. grout) can cause seepage or leakage and therefore hydraulic short circuits.

Table 2 gives a summary of general impacts of drilling, especially when multiple aquifers are intersected, as well as from operation of geothermal facilities. Further details are given in COSMA-1 report D 1.1.

Tab. 2: Categorization of hazardous events, related hazards and possible impacts of geothermal energy production on aquifers

Hazardous event	**Hazard**
<u>On-site:</u> - Spills / leakages above ground (contamination of the environment: biosphere, soil, groundwater)	Release of drilling fluid (TSS, salts, organic additives)
<u>During drilling (subsurface):</u> Hydraulic short circuit / annulus seepage caused by wrongly selected drilling techniques	Release of drilling fluid (see above)
Drawdown, loss of drilling fluids, subsidence due to drilling into unknown caverns, cavities or caves	Release of drilling fluid (see above), loss in quantity
Connection of two separated aquifers (leakage) caused by faulty casing, construction or plugging (sealing) and resulting hydraulic short circuit / annulus seepage, artesian groundwater outlets	Mixing of hydrochemically different groundwaters, salinization of the main aquifer (resulting from the dissolution of minerals (evaporites) or introduction of saline groundwater), loss in hydraulic conductivity by blockage of pore-space (resulting from the formation or recristallization of minerals), blow-out of gas (e.g. methane, CO_2)
<u>During operation – due to chemical incompatibilities:</u> Hydraulic short circuit / annulus seepage caused by chemical reactions of the fluids with the grouting material or casing (esp. highly mineralized water, sulfate containing waters, free carbon dioxide)	Loss in quantity or hydraulic conductivity. Sewage-related contaminants like pathogens, nutrients, trace organics (from broken sewers). Any existing contamination in the upper aquifer (industrial sites, agricultural areas), contamination of the environment (biosphere, soil, groundwater).Salinization (see above). Anti-freeze substance, e.g. glycol (additives for heat exchange fluid)
<u>During operation – due to wrong design or overuse:</u> - Not correctly sized geothermal facilities (esp. shallow geothermal facilities) Frost / thaw changes: upwarp / heaving, subsidence; shrinking of clay minerals due to dehydration: subsidence, hydraulic short circuit, contamination of groundwater	Redox-sensitive substances like Fe, Mn, released by enhanced biological activity due to higher temperatures and all other hazards mentioned above.

2 Inventory of reported hazards and hazardous events

Because of the numerous near-surface geothermal facilities compared to the rather few (but increasing) deep geothermal projects it is necessary to describe the respective impacts separately. The most reported hazardous events apply to shallow geothermal projects. These are often due to inadequately trained drill operators or technicians, wrongly selected drilling techniques, faulty casings or grouting material, not correctly sized geothermal facilities or insufficient knowledge of the geological and hydrogeological conditions.

This chapter gives some reported examples of those hazards and their impacts.

Most of them were also compiled by Steuerwald & Rumohr (2010) and the "Personenkreis Geothermie" ("expert network geothermal systems", PK Geothermie, 2011) based on a survey of the State Geological Surveys of Germany. In that study, a questionnaire based on the knowledge of experts from all federal states, standardization committees, developers, planners, drilling contractors, expert committees, consulting engineers and regulatory authorities such as environmental agencies, water authorities and mining authorities was sent to the State Geological Surveys, in order to comprise all impacts of geothermal energy. The return rate was 100% (PK Geothermie, 2011).

In most cases the drilling for borehole heat exchangers and the installation of geothermal facilities were carried out on private ground and no data on well geometry, materials used for the well construction, grouting material etc. are available. Only in a few cases there is some data available regarding the hydrogeological situation.

Nevertheless, the known cases are presented here with all publicly available data.

2.1 Reported impacts of shallow geothermal energy (< 400 m depth)

Although not all the examples presented here in any case led to a direct negative influence on a drinking water resource, these reported hazardous events can be a threat to groundwater resources due to hydraulic connections or creation of pathways for contaminants.

The known impacts on freshwater aquifers due to the exploitation of geothermal energy in Germany as well as precautions to prevent the hazardous events are summarized in tabular form in Appendix 1.

Case 1: Incorrectly sized or overuse of geothermal facilities

In Hesse, in the year 2009, incorrectly sized borehole heat exchangers and an overuse of geothermal units were reported causing unexpected changes in temperatures of the subsurface. As a consequence, heating, cooling or icing led to an upwarp and heaving of the subsurface, followed by subsidence. In some cases, undersizing or overuse of the geothermal unit led to heaving and subsidence due to frozen foundations. Frost / thaw changes can lead to pathways around the borehole heat exchanger or outlet of heat exchange fluids and therefore to hydraulic connections and contamination of groundwater, either from upper to lower aquifer or vice versa, depending on the pressure regime (Fig. 1).

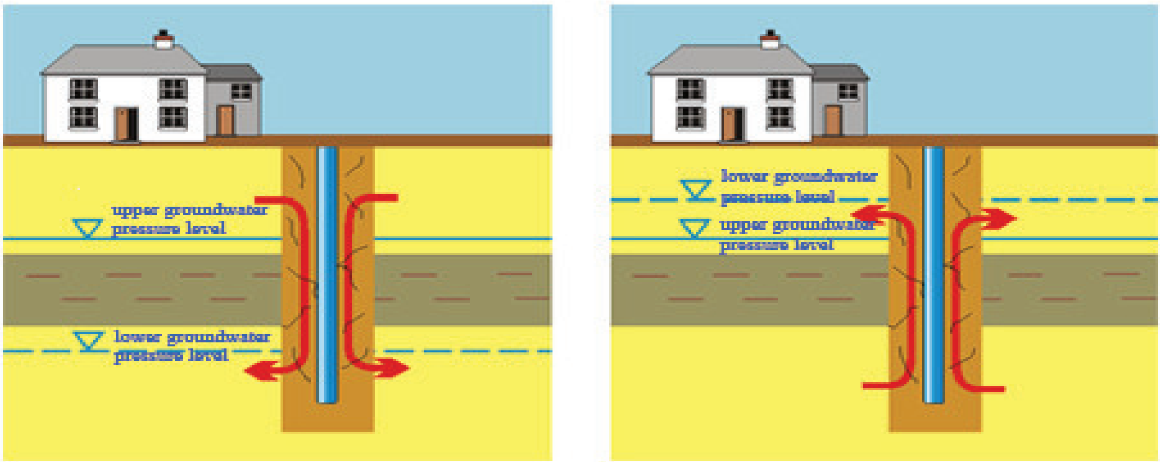

Fig. 1: Hydraulic connection of two former separated aquifers due to leakage through faulty grouting material, caused by frost / thaw changes or chemical reactions with the sealing material (modified after LAGB).

Case 2: Drawdown of groundwater due to discharge from the uppermost aquifer into an underlying aquifer

Due to hydraulic connections of primary separated aquifers by drilling, a drying up of groundwater measuring sites in Hesse (in 2009) in a distance of 200 m from the drilling site has been observed.

In Schorndorf, Baden Wurttemberg (in 2008), where the depth of drilling was about 115 m, as well as in Renningen, Baden Wurttemberg (in 2011) a drying up of groundwater wells nearby occurred after drilling. The drilling caused a drawdown of groundwater because of a discharge from the uppermost aquifer into an underlying aquifer.

Case 3: Subsidence

Besides a drawdown of groundwater, in Schorndorf, Baden Wurttemberg (2008) subsidence was observed due to mass losses according to hydraulic connections between two separated aquifers.

In Leonberg - Eltingen, Baden Wurttemberg (2011), subsidence occurred after drilling of an 80 m depth deep borehole for a heat exchanger system. The reason was probably drilling into an unknown cavity.

By inadequate sealing of the annular space of two geothermal boreholes in Baden Wurttemberg, an aquifer in the "Keuper" was connected with the underlying aquifer of the "Muschelkalk". The consequences were subsidence, increased pressure levels in the deeper aquifer, mixing of fluids and changes of groundwater flow directions.

<u>*Case 4: Artesian groundwater outlets*</u>

In Hesse, some artesian groundwater discharges have been reported, amongst others in 2009 in Wiesbaden, causing a flooding of adjacent streets.

In one case, the reason was an inadequate, not stable sealing of the borehole, probably caused by frost / thaw changes and incorrectly sized borehole heat exchangers.

In some cases, ascending groundwater led to the mobilization of fine particles and suffusion causing the risk of subsidence and groundwater contamination due to hydraulic leakage (Fig. 2).

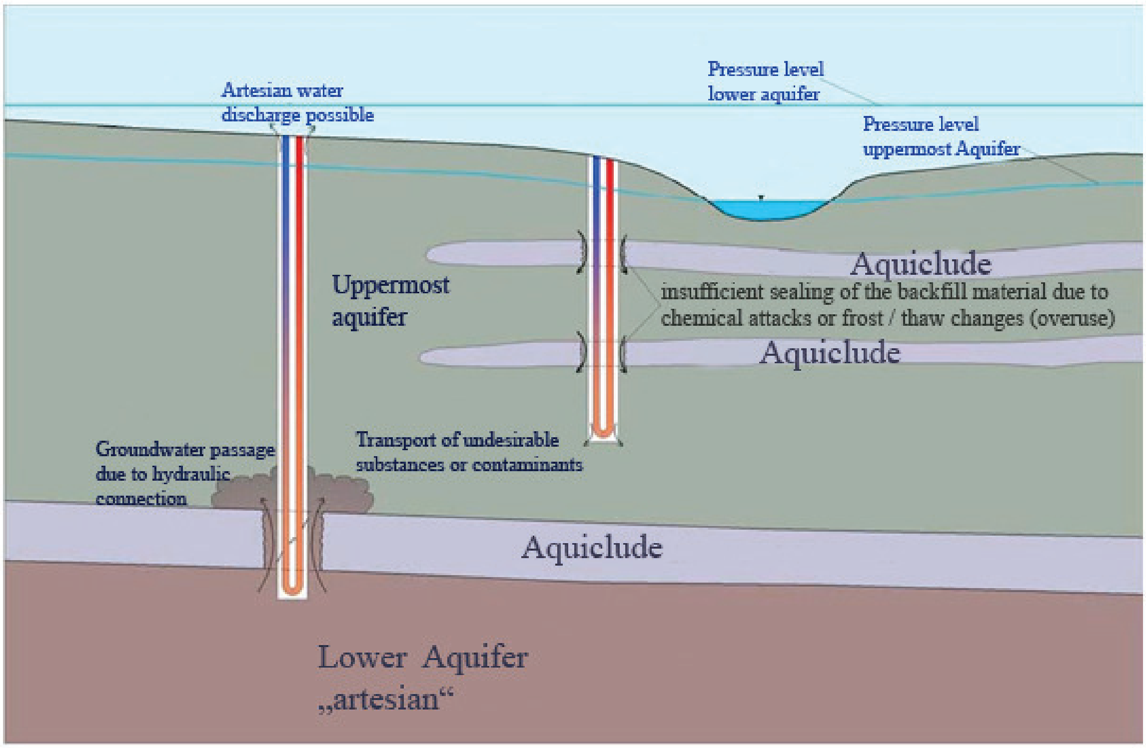

Fig. 2: Potential risks due to hydraulic connections of former separated aquifers, artesian groundwater and seepage through backfill material caused by frost / thaw changes (overuse of heat exchangers) or "chemical attacks" (modified after LBEG in: PK Geothermie, 2011).

<u>*Case 5: Transfer of contaminants*</u>

In Saxony-Anhalt, a review of geothermal heat exchanger boreholes has shown that the backfilling of the boreholes had no seals but only a gravel pack. As a consequence contaminants (hydrocarbons) were transferred from the uppermost into the deeper aquifer through the annulus of the boreholes (Fig. 3).

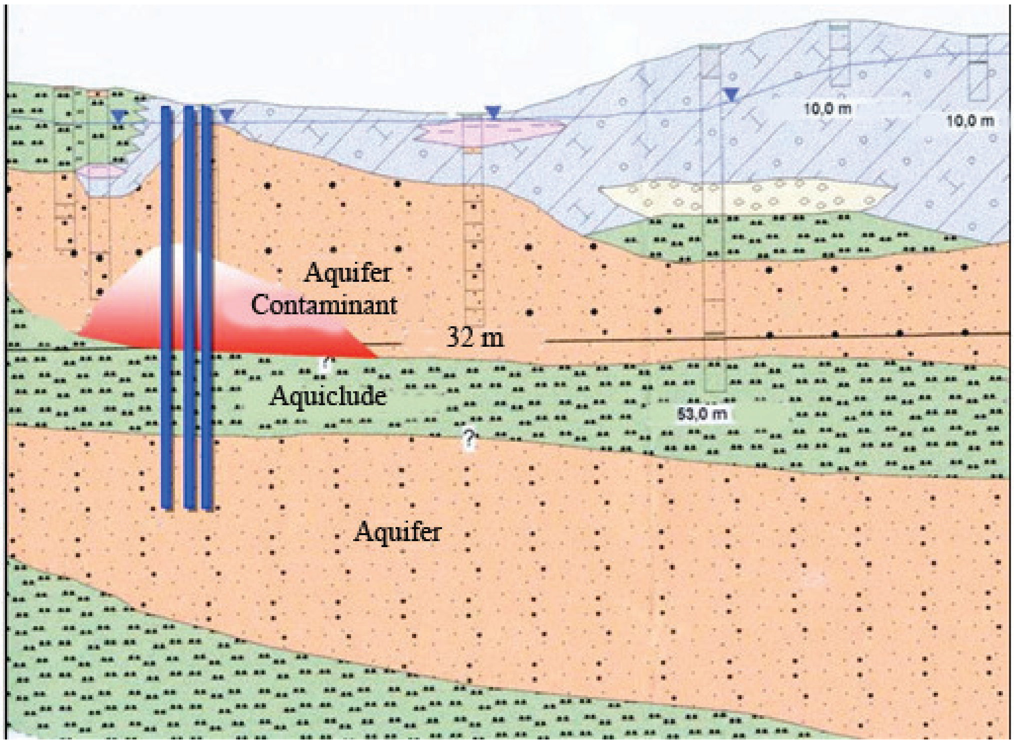

Fig. 3: Transfer of contaminants (hydrocarbons) caused by wrongly selected backfill material (modified after LAGB in: PK Geothermie, 2011).

Furthermore, inadequate sealing or backfilling of boreholes can cause a transition of heat transfer fluids (e.g. glycol) into the aquifer, in case of a leakage of the heat exchanger (see also Report D 1.1).

Case 6: Swelling and heaving of bedrock due to water seepage

The best known example of a hazardous event due to leaky annular space fillings of geothermal heat exchanger boreholes are the damages in Staufen / Breisgau, Baden-Wurttemberg (2007). Here, ascending groundwater through the annulus of the drilling of the heat exchanger reached into sulphate bearing layers (anhydrite) of the “Gipskeuper”-Formation, also containing clay minerals. The main stratigraphic units in the area of the drillings are listed in Table 3.

The seepage induced a swelling of clay minerals and the conversion of anhydrite to gypsum, accompanied by a substantial increase in volume. The chemical reaction with an increasing volume of up to 61 % (due also to the presence of clay minerals) can be described as follows:

$$\underset{\text{anhydrite}}{CaSO_4} + 2\,H_2O \;\; \text{->} \;\; Ca_2^{+} + SO_4^{2-} + 2\,H_2O \;\; \text{->} \;\; \underset{\text{gypsum}}{(Ca[SO_4] * 2\,H_2O)}.$$

Tab. 3: Stratigraphic units in the area of the drillings for geothermal heat exchanger in Staufen (after LGRB 2009)

Abbr.	**Formation**	**Sub-Formation**	**Lithology (main comp.)**	**Approx. depth**
km	Mittelkeuper		Claystone, dolomite	
km2	**Schilfsandstein**			
DM		Dunkle Mergel		
km2s		Schilfsandstein		
km1	**Gipskeuper**			
OBE		Obere Bunte Estherien-Schichten		
GES		Graue Estherien-Schichten		
UBE		Untere Bunte Estherien-Schichten	Claystone, dolomite	-20.60 m
MGH		Mittlerer Gipshorizont	Claystone, gypsum	-59.00 m
WEH		Weinsberg-Horizont	Claystone, gypsum	-69.00 m
DRM		Dunkelrote Mergel	Claystone, gypsum, anhydrite	-83.50 m
		(Entringen-Sulfat)		
BH		Bochingen-Horizont	Claystone, anhydrite	-92.50 m
GI		Grundgipsschichten	Gypsum, anhydrite, claystone, dolomite	- 114.50 m
ku	**Unterkeuper**		Dolomite, marlstone, claystone	-122.30 m
GRE	Grenzschichten			
Gd		Grenzdolomit		

A schematic geological profile of the different layers is given in Fig. 4.

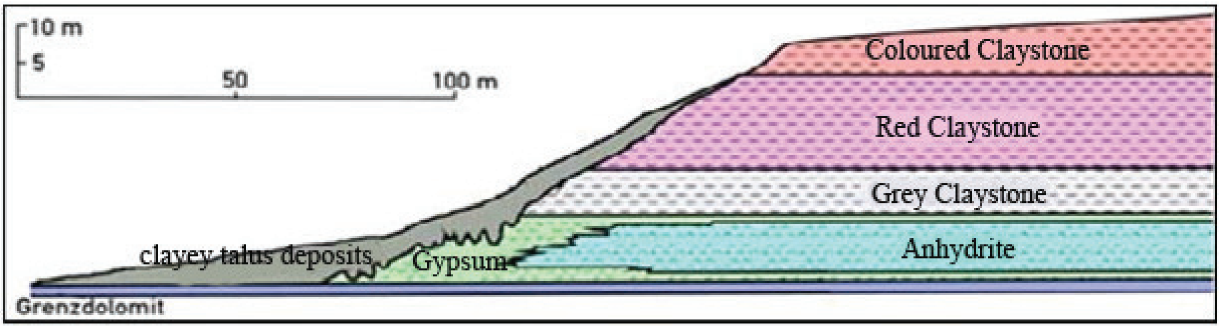

Fig. 4: In the case of a low coverage, anhydrite will be completely dissolved and recrystallized as gypsum. Potential hazards exist due to leaching of gypsum and subsequent subsidence (left). Under a thick coverage anhydrite remains in its crystalline structure (right). Here, a potential risk is the contact with water and an increase in volume caused by gypsum formation, due to lateral seepage through the annulus (modified after PK Geothermie, 2011).

The formation of gypsum begins with the dissolution of anhydrite, followed by the recrystallization of gypsum by incorporation of H_2O into the crystal lattice. Here, clay minerals, especially montmorillonite, illite and vermiculite, play an important role as they swell and therefore widen the anhydrite structure, creating better pathways for the fluid.

Studies on the swelling behaviour of anhydrite and argillaceous rocks were carried out for example by Reimann (1991) and Rauh (2009).

In Staufen, a total of seven boreholes for heat exchanger systems were drilled up to 140 m depth within an area of about 330 m² in the city center at the Town Hall.

First damages of buildings occurred a few weeks after the drilling of the geothermal boreholes.

XRD – analyzes of the cement of the annular space has shown a very high content of ettringite ($Ca_6Al_2[(OH)_{12}|(SO_4)_3]\cdot 26\ H_2O$), characterized by a high water content, extremely low density and very high porosity. The water-rich ettringite was build under increasing volume due to the contact of the cement-sealing with pore water and sulfate of the gypsum and anhydrite bearing layers. By the "sulfate-attack" the structure of the former cement within the annular space has broken and therefore has been less stable and more permeable (LGRB 2010, 2012).

Therefore, the hazardous event in Staufen is probably due to the usage of unsuitable cement that was not sulphate resistant.

By geodetic measurements, an elliptical elevation region with a length of about 280 m and a width of about 180 m was determined. The maximum continuous uplift rate in the uplift center is up to 11 mm / month (PK Geothermie, 2011) but after remediation measures (groundwater drainage) it was reduced to 4 mm / month in January 2012 (LGRB 2012).

Further seepage of groundwater into the swellable rock layers could be prevented, but the swelling process may continue as long as residual water is in contact with anhydrite.

Case 7: Suffusion, subsidence and collapse

During drilling of a borehole of 70 m depth for a heat exchanger system in Kamen-Wasserkurl, North Rhine – Westphalia (2009) a subsidence occurred, followed by a collapse creating a sinkhole of a volume of 50 – 60 m^3 (Wrede et al., 2010; PK Geothermie, 2011).

A groundwater monitoring programme showed that groundwater, together with significant amounts of sediment, discharged through the open borehole from the first aquifer into deeper karstified strata (Fig. 5).

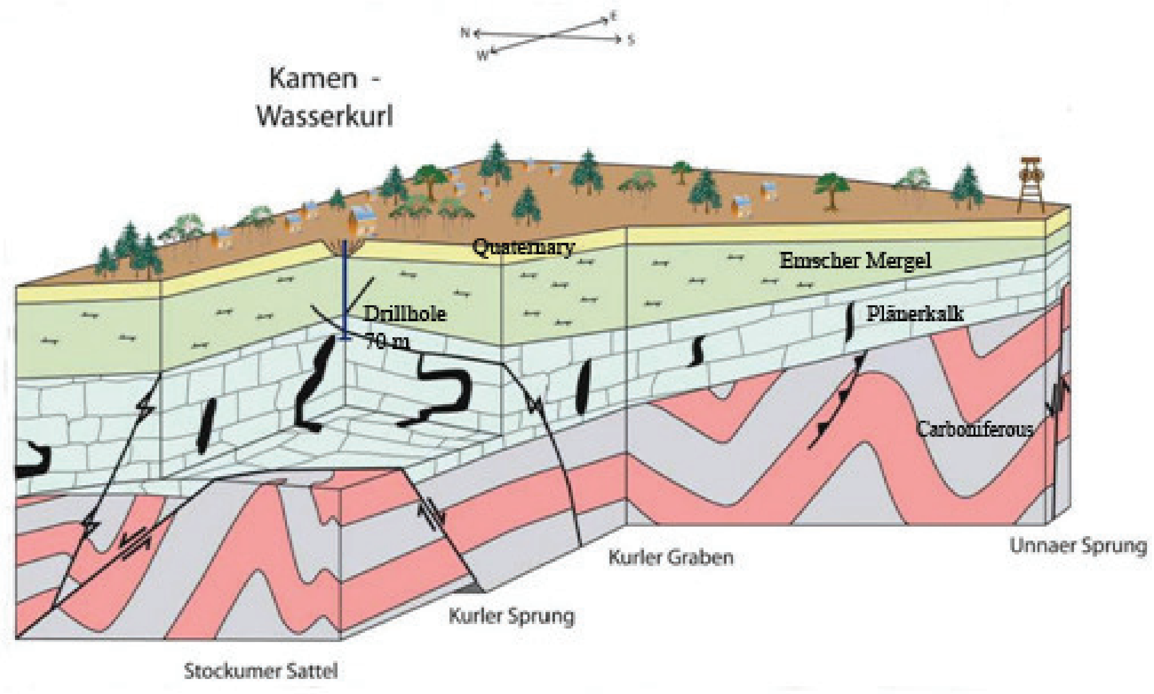

Fig. 5: Schematic representation of the geological situation in Kamen-Wasserkurl (modified after GD NRW, in: PK Geothermie, 2011).

At the depth of 70 m the drilling reached the transition zone of the “Emscher-Mergel” (marl) to the rocks of the “Plänerkalk” (limestone) with pervious faults, interconnected with karst cavities of large volumes within the “Plänerkalk”. The loss of drilling fluid was balanced with a continuous groundwater inflow from the Quaternary aquifer. This was due to the lack of the sealing of the borehole against the quaternary aquifer. After the withdrawal of the drill pipe the groundwater discharged into the borehole together with large volumes of sediment and flowed through the drilled fracture system into the karst cavities of the rocks of the “Plänerkalk”-Group.

Subsequently, the mass transfer within a tectonically dominated fault system led to the collapse and finally to a sinkhole at the surface

Around the drilling site a considerable groundwater lowering was recognized. An impact on the quality of groundwater resources used for drinking water has not been reported, but due to the karstic environment a change of groundwater flow directions occurred.

Case 8: Contamination of surface water and / or groundwater by surface spills

Contamination of surface water or groundwater due to an uncontrolled discharge of drilling fluids is often reported. As an example, in Hesse an unnoticed subsurface discharge of drilling fluids led to a contamination of surface water in a distance of about 500 m due to effluent hydraulic conditions, resulting in increasing turbidity of the surface water.

Such hazardous events can also be a potential threat to groundwater resources, especially if there are pathways to deeper aquifers like fractures.

Case 9: Outgassing [Saarland, Baden Wurttemberg]

By unexpected geological conditions, drilling into gas reservoirs can cause a blow-out or a contamination of groundwater by leaking borehole seals.

Some examples of outgassing are known in Saarland and Baden Wurttemberg. Methane gas leaks are reported from the coal-bearing strata of the Carboniferous Age in Saarland and from the "Opalinuston" in Baden-Wurttemberg as well as from the Upper Tertiary in the Upper Rhine Graben. In some regions of the Saarland, especially in Saarbrucken, methane gas leaks are well known. Here, drilling is approved only with special requirements.

Another, but totally unexpected case of outgassing of methane gas occurred on the northern edge of the "Alb" in Baden Wurttemberg. Here, at a drilling of about 100 m depth for a heat exchange system, a methane gas reservoir was found within the "Opalinuston" (clay stone). The borehole had to be closed.

Methane gas leakage in boreholes can lead to explosions at volume concentrations of 4.4 – 16.5 %, higher concentrations with appropriate supplies can lead to longer lasting fires (PK Geothermie 2011).

Also in Baden Wurttemberg, in the area of the Rottenburg flexure, carbon dioxide escaped from rocks of the "Muschelkalk" through the annulus of the borehole and two faulty probe tubes. In this case, the system had to be abandoned and dismantled.

2.2 Reported impacts of deep geothermal energy (> 400 m depth)

From deep geothermal reservoirs in Germany, no case is known or published that due to any kind of exploration, installation or operation activities a negative impact on shallow drinking water resources occurred. Main reason for that is the fact that mining authorities permit the rights for deep well bores to be used for geothermal energy exploitation only if safety for shallow groundwater can be assured. Where the drinking water could be at risk, geothermal energy production is not permitted or carried out. In general it can be said that the permission process through the competent authorities administer safety and ensures that negative impacts of geothermal energy production has no negative impacts on shallow drinking water reservoirs. Furthermore, drilling companies engaged in deep drilling projects are certified and have well trained staff and technicians.

On the other hand, until now there are a only a few deep geothermal projects in Germany in operation (about 20 in 2012). Therefore no impacts on drinking water resources have been reported so far.

Four cases are described in the following which are published in the literature about incidents of deep geothermal energy exploitation from sites outside Germany.

Case 1: Shallow aquifer contamination due to pond and pipeline spill

In the area of the Los Azufres geothermal field (Mexico), surface water and shallow aquifers were contaminated due to the exploitation of deep brines (Birkle & Merkel 2000). The sources of contamination were leaking evaporation ponds and pipelines, overflowing of reinjection wells and pond rims and outflowing of brines during rehabilitation or drilling operations (Birkle & Merkel 2000). Due to that, increased concentrations of the elements Fe, Mn, F, B, and As were observed for example in surface waters within the geothermal field as well as up to 10 km outside. The discharge of hypersaline geothermal brines also causes salinization of surrounding soils. Such contaminations could easily be prevented by the use of a closed geothermal production cycle and direct reinjection of the brines as it is state of the art. Birkle & Merkle (2000) point out clearly that in the case of Los Azufres the environmental impacts are due to the poor technical and administrative operation.

Case 2: Groundwater contamination due to natural flow and spill from operation

The Balcova Geothermal Field located in Izmir, Turkey is situated on an east-west directed graben plain within which hot water reaches the surface from a fault zone (Aksoy et al., 2009). The geothermal water cycles along the immediate vicinity of the Agamemnon fault mixes with cold waters at different depths of this fractured zone. Aksoy et al. (2009) found out that the hot geothermal water and the cold regional groundwater resources of the shallow aquifer mix due to natural and anthropogenic reasons including (i) natural upward movement of geothermal fluid along the fault, (ii) leakage of fluid from faulty constructed boreholes, (iii) wrong reinjection management; and, (iv) uncontrolled discharge of waste geothermal fluid to the natural drainage trenches. As a result the cold groundwater reserves of the shallow aquifer are contaminated thermally and chemically in such a way that various toxic chemicals including arsenic, antimony and boron are introduced to the heavily used surficial aquifer waters preventing their use for human consumption and agricultural irrigation. Groundwater contamination which is due to the anthropogenic activities can be avoided with proper installation, management and monitoring.

Case 3: Induced seismicity due to stimulation at Soultz-sous-Forêts

Several deep wells were drilled in the Rhine Graben (Soultz-sous-Forêts, France) to evaluate the geothermal Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS) potential of a deep fractured granite reservoir (Charléty et al., 2007). Stimulations of three main boreholes were carried out, which reached about 5 km depth, intersected a crystalline basement overlain by 1.4 km of Cenozoic and Mesozoic sediments. During these stimulations and other hydraulic activities, a seismological surface network was installed in order to monitor the seismicity induced by the massive fluid injection. Charléty et al. (2007) show that the largest events recorded on the site occurred after the shut-in. Their spatial distribution appears not to be random within the reservoir, and the focal mechanisms of these events also confirm the non-randomness of their distribution. They conclude that the behaviour of the reservoir is controlled by the main fractured zones, which either lead the fluid or hinder its path. From this very deep (> 4km) enhanced geothermal reservoir no impacts on shallow groundwater due to the stimulation activities are known or have been detected.

Case 4: Induced seismicity due to re-injection at field The Geyser

Water injection into geothermal systems has often become a required strategy to extend and sustain production of geothermal resources. Majer and Perterson (2007) show that operators of the Geyser field in California, USA, have been injecting steam condensate, local rain and stream waters, and most recently treated wastewater piped to the field from neighbouring communities to reduce a trend of declining pressures and increasing non-condensable gas concentrations in steam produced. They show that seismicity has increased due to increased injection but it has been found to be somewhat predictable (Majer and Peterson 2007). That the water injection is probably not totally beneficial is only related to the performance of the reservoir but not with regard to the influence on shallow groundwater. The injected water may migrate along major fractures and quickly reach production wells, which may degrade production by lowering fluid enthalpy and temperature.

Many more incidents of induced seismicity are discussed in pertinent scientific journals (compare Evans et al., 2012 and Majer et al., 2007) as well as the newspapers if the respective earth movements were felt by the public. For Germany cases are reported for geothermal plants at Unterhaching (Bavaria, 2008: magnitude 2.5), Insheim (Rhineland-Palatinate, 2010: magnitude 2.4) and Landau (Rhineland-Palatinate, 2009: magnitude 2.7). Furthermore, seismic events are reported from sites outside Germany like Basel (Switzerland, 2006: magnitude 3.4). In the following some more general findings are listed with regard to induced seismicity.

Evans et al. (2012) published a comprehensive survey of the induced seismic responses to fluid injection in geothermal and CO_2 reservoirs in Europe. The paper documents 41 European case histories that describe the seismogenic response of crystalline and sedimentary rocks to fluid injection. The conclusions were made against the background that injections which involve a net fluid volume increase within the reservoir such as in hydraulic stimulation operations produce a greater disturbance of pressure in the reservoir and its surroundings than comparable injections balanced by production from the same reservoir, as is the case with most operating geothermal plants. Furthermore, most data taken into account from igneous rocks were from stimulation injections that involve a fluid volume increase in the reservoir and the vast majority of data from sedimentary rocks were from balanced circulation at operating geothermal plants. The data from Evans et al. (2012) underline the fact that injection in sedimentary rocks seems to be less seismogenic than in crystalline rocks. But there is no doubt that felt earthquakes can also occur in sediments. The risk of producing sensed events is increased with faults present near the wells. Even more explicit is their statement that any injection into crystalline rocks produces seismic events. However, the data from Evans et al. (2012) are not fully consistent with the concept that injection into deeper crystalline formations tends to produce larger magnitude events. The presented data do not show any simple relation between injection pressure and the maximum magnitude of the induced events.

Majer et al. (2007) give an overview on induced seismicity associated with EGS. The special controversial issue inherently associated with EGS is induced seismicity. It has been the cause of delays and threatened cancellation of at least two projects worldwide because of the public concern over the amount and magnitude of the seismicity associated with current and future operations. Majer et al. (2007) present several case histories and illustrate a number of technical and public acceptance issues. They conclude that EGS-induced seismicity need not pose a threat to the development of geothermal energy resources if site selection is carried out properly, community issues are handled adequately and operators understand the underlying mechanisms causing the events.

Inventory of potential impacts of deep geothermal systems in Germany

In **Germany**, some known impacts of the exploitation of deep geothermal energy are washouts and subsidence in setting the anchor tube tour and due to mass losses, contamination of groundwater by drilling fluids and unexpected geological conditions like the occurrence of hydrocarbons (gas and oil) or CO_2 gas. Furthermore, scaling can cause radioactively contaminated plant parts.

Another risk is corrosion and „chemical attacks“ against pipe materials due to aggressive fluids or components, like H_2S or CO_2, potentially causing leaky borehole sealings which could lead to seepage of geothermal brines which carry by nature substances potentially harmful for surface as well as groundwater. Further, emission of H_2S and CO_2 directly to the atmosphere leads to oxidation and subsequently acid rain is formed.

Due to an inadequate wellbore-sealing, a contamination of groundwater by chemical additives, salt water intrusion or gas escape (e.g. methane) is possible.

The latter comes back to the issue that during the drilling process one issue is to seal aquifers in different depths from each other.

Since decades research is undertaken at the GFZ about the influence of earthquakes on groundwater quality and flow. It is known that groundwater chemistry can change due to these events. Question now is if changes of the groundwater quality could even be used as an indicator for induced seismicity. This could be a study area for the future.

3 Lessons learned: precautions and countermeasures

In comparison to the deep geothermal systems considerably more shallow geothermal facilities have been installed in recent years. Figure 6 shows exemplarily the trend of approvals for the installation of Borehole Heat Exchanger (BHE) systems in Hesse from the years 1995 until 2008.

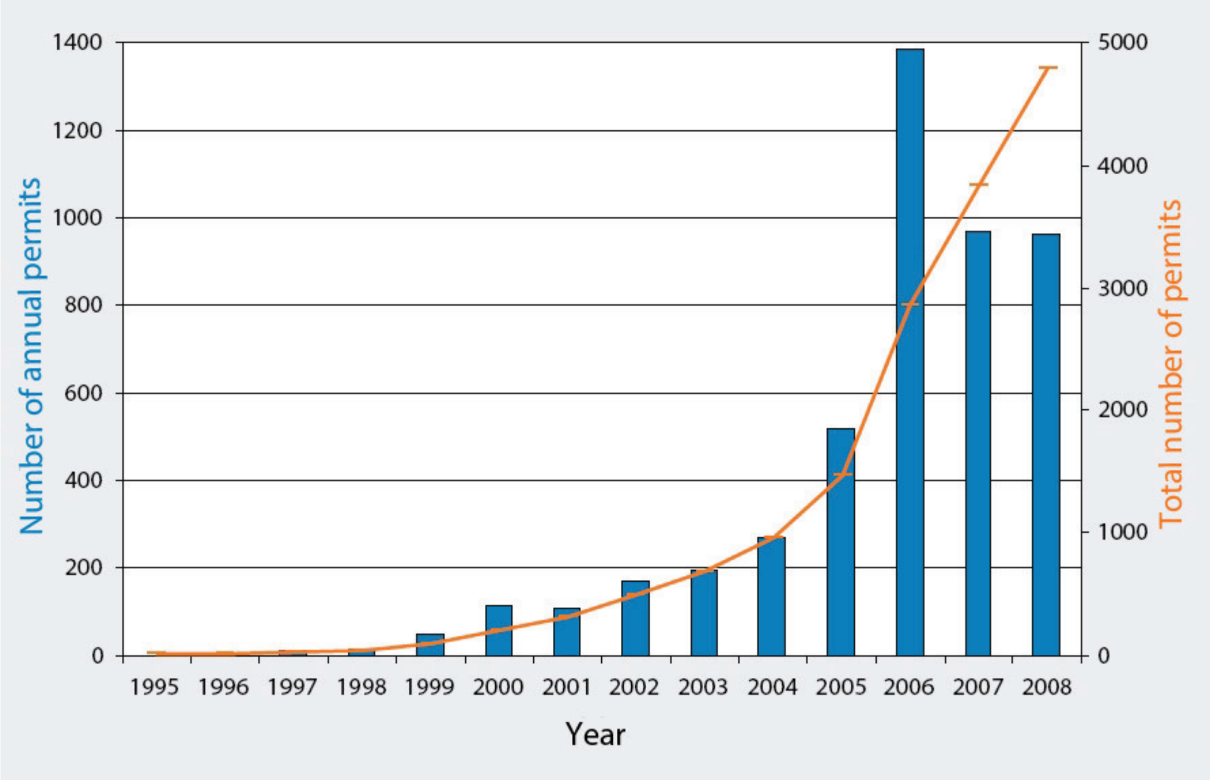

Fig. 6: Annually approved BHE systems and their total number in Hesse (modified after Rumohr, 2009; source: HLUG).

According to the “GtV-Bundesverband Geothermie” (http://www.geothermie.de/wissenswelt/geothermie/in-deutschland.html), in Germany a total of about 265,000 borehole heat exchanger systems for the use of near-surface geothermal energy (< 400 m depth) has been installed (updated: 2012) but a total of only 20 deep geothermal projects are in operating state, another 19 projects are under construction and 74 are in the planning stage (updated: October 2012).

Each drilling or subsurface activity has an impact on the environment and the likelihood of hazardous events (i.e. the risk) rises with the number of boreholes. However, it is important to note that well bore drilling activities are independent on the subsequent use of georesources (e.g. geothermal exploitation). It is the technical or engineering process itself which carries most of the risk. It is therefore necessary to identify hazards and hazardous events arising from those subsurface activities in order to minimize the risks.

In Germany, all reported hazardous events apply to shallow geothermal projects. As they are mainly failures that occur during drilling (e.g. artesian discharges, collapse, blow-outs – see appendix 1) this can usually be related to the lack of exploration of the geological subsurface. Due to the high costs of deep boreholes, deep geothermal projects must be planned carefully, including in most cases a 3D-seismic survey, to minimize the financial risks. Furthermore, there are only a few companies specialized in deep drilling with personnel trained from oil- and gas drillings. This and the detailed permission process governed by the mining authorities also reduce the likelihood of the occurrence of hazardous events, i.e. the risk. Difference between shallow and deep wells drilled is that for the latter not only the water authority needs to give permission but the mining authorities as well. The process is let by the mining authorities consulting the water board. Further, deep bore holes require a pre-assessment of environmental effects (UVP = Umweltverträglichkeitsprüfung). In opposite thereto shallow wells can just be drilled. Permission is not required but announcement with the water authority is sufficient.

Apart from insufficient knowledge of the geological and hydrogeological conditions hazardous events related to shallow geothermal systems also arise from wrongly selected drilling techniques (missing casing tubes or blow-out preventers), faulty casings or grouting material (inadequate sealing), not correctly sized geothermal facilities which can all be related to inadequately trained planners, drill operators or technicians.

Risks can be minimized considerably if the existing rules, guidelines and regulative policies (see appendix 2) are applied consequently and only certified drilling companies with well-trained staff are engaged.

Most reported hazardous events are due to insufficiently sealed boreholes or wrongly selected grouting material. Besides a detailed hydrogeological exploration (see VDI 4640, part 1 [2010]), to prevent hydraulic connections of separated aquifers it is essential to use adequate physically and chemically stable, impermeable grouting material (see VDI 4640, part 2 [2001]) as well as protective tubes during drilling, to avoid scavenging losses (see DVGW W 120). Furthermore, in some regions, where gas reservoirs could be expected, the use of gas-tight clay sealing as well as a gas monitoring is essential.

In order to surely avoid hydraulic connections between two separate aquifers the environmental authority of Berlin e.g. is limiting the depth of a borehole heat exchanger system to the uppermost aquifer. Where this is not possible the correct application of best available technologies and practices (e.g. telescope casing, pressure grouting) can ensure sufficient sealing between two different aquifers. The same is true for drillings into sulphate bearing layers. Here the seepage of groundwater or drilling fluids into swellable rocks, containing minerals like anhydrite, gypsum and clay minerals, must be avoided. Otherwise, the annulus seals need to be supplemented and the groundwater pressure levels must be reduced by hydraulic methods. Some German authorities generally recommend to avoid drilling into sulphate bearing layers (like gypsum or anhydrite).

As further precaution to obtain a permanent tightness of the annular space fillings, an appropriate size of the geothermal heat exchanger system is necessary for avoiding leakage due to frost / thaw changes within the sealing system. Some cases of damage due to not correctly sized borehole heat exchanger systems or overuse of geothermal facilities are also described by Bassetti et al. (2006). Guidelines for the correct construction and dimensioning of geothermal facilities are given in VDI 4640, part 2-4.

In general, every geothermal system has its own site-specific geological and hydrogeological conditions. It is therefore recommended to analyse the main components of the groundwater as well as the on-site parameters (temperature, pH, E_H, electrical conductivity), to assess the hydrochemical conditions and the groundwater quality. This is necessary to avoid reactions between annular cement / grouting material and groundwater and to enable the detection of mixing of hydrochemically different groundwater in case hydraulic connections do occur.

By the use of casing tubes in the upper layers of unconsolidated rocks, an uncontrolled mass transport into deeper cavities and thus subsidence and collapse can be avoided. Similarly, the flushing volumes must be continuously monitored and recorded.

In regions, where outgassing could be expected, a continuous gas monitoring must be carried out, the borehole has to be equipped with gas tight clay sealings and blow-out preventers should be on site. Furthermore, blow-out preventers should be installed on site.

In deep geothermal projects, the seismic risk can be minimized by a monitoring of the pressure levels and carefully adjusted reinjection-rates.

Table 4 gives an overview of the potential hazards due to geothermal energy mentioned above as well as precautions and countermeasures for preventing hazardous events.

Tab. 4: Potential hazards regarding geothermal energy production and possible precautions and countermeasures

Hazardous event (number of reported cases)	Precautions	Countermeasures
Usually related to drilling		
Water outlet / artesian groundwater discharge (49)	Adequate borehole sealing; use of preventer or packer; detailed hydrogeological exploration	Hydraulic methods (e.g. pressure relief wells)
Contamination of ground surface, surface water or groundwater (40)	Surface sealing of drilling site, use of protective tube to prevent scavenging losses; supply of sufficient mud tanks	Decontamination
Outgassing / blow out (7)	Use of gas-tight clay sealings; gas monitoring; detailed geological exploration	Use of blow-out preventers
Related to drilling and operation		
Upwarping / subsidence of surface, due to freezing or swelling (53)	Correctly sized geothermal facilities, no overuse of heat exchanger capacities, adequate borehole sealing;	Installation of correctly sized geothermal facilities
Transfer of contaminants, mixing of different waters (31)	Adequate borehole sealing; avoiding of drilling through impermeable layers	Hydraulic methods; decontamination
Drawdown of groundwater (11)	Limiting the depth of drilling on the uppermost aquifer; adequate borehole sealing; detailed hydrogeological exploration	
Suffusion, collapse (7)	Adequate borehole sealing; use of casing tubes; detailed geological exploration	
Uplift due to swellable rocks (clay minerals, sulphate bearing layers) (2)	Avoiding of drilling into sulphate bearing layers; detailed geological exploration	Hydraulic methods (e.g. pressure relief wells).
Related to operation		
Corrosion (42)	Use of corrosion-inhibitors	Rehabilitation
Iron clogging (17)	Closed water cycle, avoiding of aeration	Rehabilitation
Gas diffusion in PE probes (2)	Use of diffusion-resistant probe material	Venting of the fluid circuit
Scaling	Use of scale-inhibitors	Rehabilitation
Limited to deep geothermal systems		
Seismic event	Monitoring pressure levels; adjusted reinjection rates, avoid stimulation in fractured zones.	

Based on past experiences in Germany, **best practices** for shallow geothermal systems can be summarized as follows.

- Borehole heat exchangers, heat collectors and energy piles need to be installed according to the state of the art. This includes an adequate sealing which is resistant to freeze-thaw cycles and aggressive fluids. Guidelines representing the state of the art of the thermal use of the underground are published by VDI (Verein Deutscher Ingenieure; 2001, 2004, 2010).
- Furthermore, proper planning and design of geothermal facilities requires profound knowledge of the geological and hydrogeological structure of the subsurface. Drilling operations should be carried out only by experienced and well trained operators and technicians. Drilling companies must be certified.
- Most countries provide guidelines for the use of geothermal energy which describe the correct planning, secure installation and harmless operation of geothermal facilities (e.g. SenStadtUm, 2012). Moreover, State Geological Services can provide borehole data as well as geological and hydrogeological maps.
- The creation and maintenance of geothermal system registers and maps of the geothermal potential could provide additional information.
- The most difficulties in constructing geothermal facilities with respect to hydrogeological conditions arise from the presence of different groundwater layers, karstified layers or swellable rocks. The risks can be minimized by limiting drilling to the uppermost aquifer and by avoiding drilling through impermeable layers. In either case, pressure grouting must be used to ensure an adequate sealing of the well casing.
- According to the mining law (“Lagerstättengesetz”) and the Water Act (Wasserhaushaltsgesetz, WHG), geothermal projects could also be supervised more strictly by the authorities. The use of geothermal energy should not be allowed in water protection areas, as it is already the case, e. g. in Berlin.

An overview of regulations, best practices, recommendations and state of the art regarding near-surface geothermal facilities is given in appendix 2.

4 Summary

As a complement to COSMA-1 Report D 1.1, this report lists published examples of hazardous events with respect to the utilization of geothermal energy in Germany. The systems are therefore divided into near-surface (< 400 m depth) and deep geothermal energy (> 400 m depth) systems.

The impacts of near-surface geothermal systems usually concern aquifers and therefore groundwater resources. Moreover, there are considerable more shallow geothermal systems installed than deep geothermal facilities (factor 10,000 : 1). This and the fact that deep geothermal projects are in general being planned more accurately with an extensive exploration of the deeper underground using 3D-seismic processing (due to higher financial risk) result in more frequently reported hazardous events in the exploitation of shallow geothermal energy. Moreover, deep geothermal projects are supervised more strictly by the mining authorities. The drilling process in particular requires permission by the authorities what is not necessary for shallow wells which only need to be announced.

The inventory of reported hazards and hazardous events presented in this paper is based on a survey of the “PK Geothermie” (2011) as well as collected and evaluated data of the State Geological Surveys in Germany, interviews and a literature review in German and International Technical and Scientific journals.

It has been shown that most of the reported incidents were due to leakage or seepage of groundwater or drilling fluids through insufficiently sealed boreholes or wrongly selected or faulty grouting material resulting e.g. in artesian discharges, contamination of surface- or groundwater or upwarping / subsidence. Often, the reported hazardous events are also due to unknown or unexpected geological and hydrogeological conditions because of insufficient geological exploration. In many cases, a combination of different causes provokes unexpected impacts or hazardous events.

Well bores and fractures are the most important migration pathways to be taken into account with regard to contamination of shallow groundwater. Both introduce the largest geological risks for a certain location.

Although this study concentrated on geothermal energy applications we would like to emphasize that many impacts described here were caused by drilling. Therefore, these risks can be described as general risks with respect to any subsurface activity and usage of any kind of georesource.

Finally, on the basis of the hazardous events and their impacts described above, some recommendations are given to prevent such unexpected events. Among these preventive actions are a detailed hydrogeological exploration, the use of protective tubes and adequate borehole sealings as well as the correct dimensioning of geothermal facilities. Detailed technical guidelines describing the state of the art with respect to the usage of near surface geothermal energy are given especially in VDI 4640 part 1-4 (2001-2010).

In some cases, possible countermeasures are also mentioned. These include hydraulic methods (e.g. pressure relief wells), the use of blow-out preventers and decontamination of polluted environments.

Given the vast number of boreholes for the usage of shallow geothermal energy, the number of reported hazardous events (not more than 0.4 %) is relatively low (see appendix 3). If the existing guidelines (see appendix 2) are consequently applied, the risks in the use of geothermal energy can be reduced significantly.

Best practices can be summarized as follows:

- Detailed hydrogeological exploration
- Hydrogeochemical investigations
- Correct sizing of geothermal facilities
- Certified and well trained drilling operators and technicians must be commissioned
- Adequate borehole sealing must be ensured
- Regulations, best practices and state of the art in terms of geothermal facilities must be observed

- Pressure levels must be monitored for adjustment of reinjection rates (use of deep geothermal energy).

In the most cases hazardous events occurred because existing technical guidelines, representing the state of the art, were ignored, or unqualified drilling companies with inexperienced operators and technicians were engaged.

Each drilling or subsurface activity has an impact on the environment and the likelihood of hazardous events (i.e. the risk) rises with the number of boreholes. Risks can be minimized considerably if the existing rules, guidelines and regulative policies are applied consequently and only certified drilling companies with well-trained staff are engaged.

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6 Appendices

Appendix 1: Known impacts due to exploitation of geothermal energy in Germany

Reported Hazard	Cause	State	Shallow (S) / Deep (D) geothermal energy	Precautions	Year of occurrence	Reference (State Geological Services) / (location)
Upwarping / subsidence of surface	Undersizing or overuse of geothermal unit; formation of ice **or** frozen ground	Hesse	S	Correctly sized geothermal facilities	2009	HLUG
Drawdown of groundwater	Discharge from the uppermost aquifer into an underlying aquifer (hydraulic connection)	Hesse	S	Limiting the depth of the drilling on the upper aquifer	2009	HLUG
Drying-up of wells		Baden - Württemberg			2011	LGRB (Renningen)
Subsidence, damage of buildings, mixing of fluids, changes of groundwater flow directions	Increased pressure levels in the deeper aquifer due to hydraulic connections to an overlying aquifer, due to inadequate sealing of the annular space	Baden - Württemberg	S	Limiting the depth of the drilling on the upper aquifer	2008 2011	LGRB Schorndorf (115 m) Leonberg (80 m)
Artesian groundwater outlets	Inadequate sealing	Hesse	S	Use of adequate, physically and chemically stable, impermeable backfill material; preventer	2009	HLUG
Transfer of contaminants	None or inadequate sealing	Saxony-Anhalt	S	Avoiding of drilling through impermeable layers	Not reported	LAGB

App. 1 (continued): Known impacts due to exploitation of geothermal energy in Germany

Reported Hazard	**Cause**	**State**	**Shallow (S) / Deep (D) geothermal energy**	**Precautions**	**Year of occurrence**	**Reference (State Geological Services) / (location)**
Swelling and heaving of bedrocks	Ascending groundwater through the annulus of the drilling into sulfate – bearing layers (anhydrite)	Baden - Wurttemberg	S	Use of adequate physically and chemically stable, impermeable backfill material	2007	LGRB Staufen (140 m)
Subsidence, suffusion, collapse	Groundwater flow from the upper aquifer into karst cavities due to missing borehole sealing	North Rhine - Westphalia	S	Limiting the depth of the drilling on the upper aquifer	2009	GD NRW Kamen-Methler (70 m)
Contamination of surface water or groundwater	Discharge of drilling fluids into surface water after subsurface transport	Hesse	S	Use of protective tube to prevent scavenging losses	Not reported	HLUG
Methane gas escapes	Unexpected geological conditions	Saarland, Baden - Wurttemberg	S	Use of gas-tight clay-sealings, gas monitoring	Not reported	LUA LGRB
CO2 gas escapes	Escape of gas through annular space	Baden - Wurttemberg	S	Use of gas-tight clay-sealings; monitoring	Not reported	LGRB
Subsidence	Washouts and subsidence in setting the anchor tube tour; unexpected geological conditions	General risk	D	Detailed geological and seismic exploration		
Contamination of groundwater due to mud losses	Fractures, caverns; unexpected geological conditions	General risk	D	Detailed geological and seismic exploration		
Hydrocarbons (gas, oil), CO2 gas	Unexpected geological conditions	General risk	D	Detailed geological and seismic exploration		

App. 1 (continued): Known impacts due to exploitation of geothermal energy in Germany

Reported Hazard	**Cause**	**State**	**Shallow (S) / Deep (D) geothermal energy**	**Precautions**	**Year of occurrence**	**Reference (State Geological Services) / (location)**
Subsidence due to mass losses	Mass losses due to production without reinjection	General risk	D	Reinjection of produced water to maintain the reservoir pressure		
Scaling: radioactively contaminated plant parts	Highly mineralized water, brines, mineral precipitation	General risk	D	Use of scale inhibitors		
Corrosion	aggressive fluids or components, esp. H2S	General risk	D	Selection of material depending on the expected chemical composition of the fluids		
Seismic risk: e.g. Unterhaching (2008: magnitude 2.5), Landau (2009: magnitude 2.7), Insheim (2010: magnitude 2.4)	Changes of the in situ rock stresses due to drilling, fracturing or fluid injection	Bavaria (Unterhaching) Rhineland-Palatinate (Landau, Insheim)	D	Monitoring of pressure levels; adjusted reinjection rates	2008 2009 2010	LfU, LIAG Unterhaching LGB Landau Insheim

Appendix 2: Regulations, best practices and state of the art regarding near-surface geothermal facilities

Case / Phases	**Regulations / Guidelines**	**References**	**Comments**
Planning and construction phase			
- evaluation of the subsurface and the geological and hydrogeological conditions	DVGW W 110, DVGW W 101	VDI 4640 Part 1	Assessment of geological and hydrogeological risks, site and/or underground contamination, (old) mining sites, sensitive groundwater uses, groundwater storeys
- evaluation of the hydrochemical composition of the groundwater	DIN 50930, part 1-5, DIN 4030, part 1-2	VDI 4640 Part 2	Assessment of the scaling and corrosion potential of groundwater
- use of water hazardous substances	VAwS – Regulations for the use of water hazardous substances, DVGW W 116	LAWA 2001, VDI 4640 Part 1	Regulations for the use of water hazardous substances, use of mud additives
- mechanically driven drilling operations	German Resources Act (Lagerstättengesetz), DVGW W 120	VDI 4640 Part 1	All mechanically driven drilling operations must be notified to the relevant Geological Survey
- drilling and well construction	DVGW W 120, VDI 4640 Part 2	VDI 4640 Part 2, DVGW W 120	Requirements for drilling and well construction
- planning, construction and operation of energy extraction facilities	Water Law (Wasserhaushaltsgesetz), German Federal Mining Act (BBergG), LAWA 2002, DIN 8901	LAWA 2002, VDI 4640 Part 1, SenStadtUm (2012)	Requirements for drilling, requirements for geothermal heat pumps, environmental aspects
- drilling depth > 100 m	BBergG	VDI 4640 Part 1	For boreholes over 100 m in depth there are mining regulations to be observed
- sealing of the borehole’s annular space	VDI 4640 Part 2	VDI 4640 Part 1-4	Sealing of the borehole’s annular space must be carried out and documented carefully; requirements listed in VDI 4640 Part 2
Operating phase			
- operation of geothermal facilities	Water Law (Wasserhaushaltsgesetz), VDI 4640	VDI 4640 Part 1	Construction or operation of geothermal facilities may require a permit pursuant to WHG
- thermal impacts on the subsurface and groundwater	VDI 4640	VDI 4640 Part 1-2, Jesußek et al. (2013)	Considerable changes in groundwater temperature have to be avoided

Appendix 3: Known impacts and hazardous events of geothermal projects in Germany according to a questionnaire to the State Geological Services (SGD), as reported in February 2011 (modified after PK Geothermie 2011)

		Number of known impacts **(according to questionnaire)**	**Remarks** (Timescale)
1	**Impacts on groundwater**		
1.1	*Hydraulic impacts*		
1.1.1	Drawdown	**11**	Short-term to long term
1.1.2	Elevation / rise	**7**	*Usually not noticed immediately*
1.1.3	Water outlet / artesian discharge	**49**	**Sudden event**
1.2	*Hydrochemical impacts*		
1.2.1	Mixing of different waters	**13**	*Usually not noticed immediately*
1.2.2	Mineral precipitations	**1**	*Usually not noticed immediately*
1.2.3	Dissolution / mobilization	**1**	*Usually not noticed immediately*
1.2.4	Input of contaminants	**17**	*Usually not noticed immediately*
1.3	*Thermic impacts*		
1.3.1	Heating	**1**	*Usually not noticed immediately*
1.3.2	Cooling	**9**	*Usually not noticed immediately*
1.4	*Biological impacts*	**0**	*Usually not noticed immediately*
2	**Impacts on the subsurface**		
2.1	*Ground heaving*		
2.1.1	Swelling processes / formation or recrystalization of minerals	**2**	*Usually not noticed immediately*
2.1.2	Icing	**38**	*Usually not noticed immediately*
2.2	*Subsidence*	**15**	Short-term to long term
2.3	*Suffosion*	**2**	Short-term to long term
2.4	*Landslides*	**0**	
2.5	*Breaking-in / collapse*	**5**	**Sudden event**
2.6	*Outgassing / Blow out*	**7**	**Sudden event**
3	**Impacts on the environment**		
3.1	*Pollution of surface water*	**16**	Short-term to long term
3.2	*Pollution of ground surface*	**24**	Short-term to long term
4	**Impacts on systems engineering**		
4.1	*Gas diffusion in PE-Probe*	**2**	Short-term to long term
4.2	*Iron clogging (Injection well)*	**17**	Short-term to long term
4.3	*Corrosion (Heat exchanger)*	**42**	*Mostly not being noticed immediately*

Comment: Based on a questionnaire to the State Geological Surveys and the Water Authorities in Germany with a return rate of 100% there is a total of 279 (see Table above) registered impacts and hazardous events due to the use of shallow geothermal energy. According to PK Geothermie (2011) the assumed number of shallow geothermal facilities was 70,000 (February 2011). This means that in less than 0.4% of shallow geothermal projects a hazardous event has been reported.

Nevertheless, it should be noticed, that the total number of smaller hazardous events is not known (PK Geothermie 2011).