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Evaluation of expert reports to quantify the exploration risk for geothermal projects in Germany

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Abstract

The development of deep geothermal energy sources in Germany still faces many uncertainties and high upfront investment costs. Methodical approaches to assess the exploration risk are thus of major importance for geothermal project development. Since 2002, expert reports to quantify the exploration risk for geothermal projects in Germany were carried out. These reports served as a basis for insurance contracts covering the exploration risk. Using data from wells drilled in the meantime, the reports were evaluated and the stated probabilities compared with values actually reached.

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Keywords: Geothermal projects; Germany; exploration risk; evaluation

1. Introduction

Though Germany lacks high enthalpy resources, a considerable increase in deep geothermal energy use has taken place since 2000. Besides numerous smaller geothermal installations such as spas and greenhouses, 24 larger plants for district heating and/or power generation are presently in operation and several further plants under construction or in the planning [1]. Fig. 1 shows the regions of hydrothermal potential and geothermal installations in Germany. Project development to date concentrates in regions with favorable conditions, namely the South German Molasse Basin and the Upper Rhine Graben.

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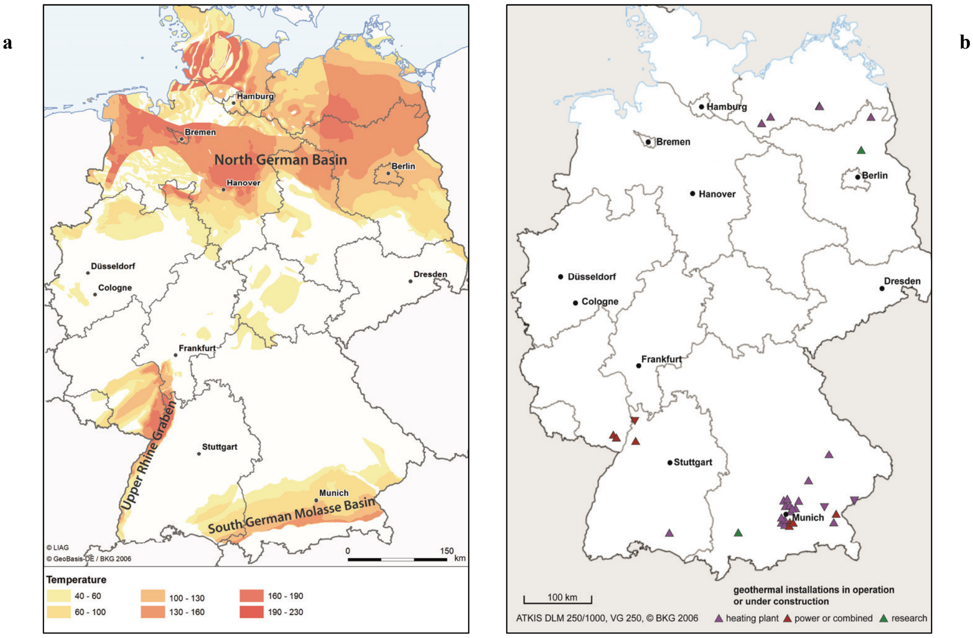

Fig. 1. (a) Regions with hydrothermal resources (proven and assumed) and associated temperature ranges in Germany (map adapted from [2]; © 2014 Leibniz Institute for Applied Geophysics); (b) heating and power plants in operation and under construction in Germany in 2015 (adapted from the Geothermal Information System for Germany www.geotis.de [3], download 7 May 2015). Base maps: © GeoBasis-DE/ BKG 2006.

On the other hand, the development of deep geothermal projects comes along with many uncertainties and considerable investments. The quantification of the exploration risk is thus of key importance for the further development of geothermal energy. A simple method to quantify the probability of success (POS) for geothermal wells is to determine the single risks for temperature and flow rate and calculate the overall probability by multiplying the individual probabilities [4]. Based on this method, 58 expert reports to assess the exploration risk for geothermal projects in Germany as a basis for insurance contracts were carried out. The studies provided an assessment of the prospect to reach defined temperatures and minimum flow rates at the examined sites. These parameters define the exploration risk for geothermal wells (see 3.1).

At several previously examined sites, wells have been completed in the meantime. Data from these wells was now used to compare the stated probabilities with actually reached values.

2. Evaluation of expert reports for geothermal projects

The first expert reports to quantify the exploration risk were requested shortly after the Renewable Energy Sources Act came into effect in 2000, the German Government´s central instrument to promote the development of renewable energies. Based on a study from 2003, the geothermal heat and power plant at Unterhaching near Munich was the first project to contract an insurance covering the exploration risk for the plant´s first well [5]. Subsequently, over 30 projects in the planning commissioned one or more studies to assess the probability of success for a geothermal well as a basis for insurance contracts. The 2004 amendment of the Renewable Energy Sources Act guaranteed higher feed-in tariffs for geothermal electricity. With increasing project activities in the following years, a strong request for assessments of the exploration risk from 2006 to 2010 culminated in a maximum of 16 studies in 2009 (Fig. 2). Since 2011, interest in the expert reports has decreased.

The examined project sites concentrated in the Upper Rhine Graben and in the Molasse Basin; only one study was carried out for a project in Northern Germany which is still in the planning phase. As the assessment of the probability of success was usually only valid for a project´s first well, the total number of wells used for the evaluation was restricted to 14, while the total number of wells drilled at the examined sites was about twice as high.

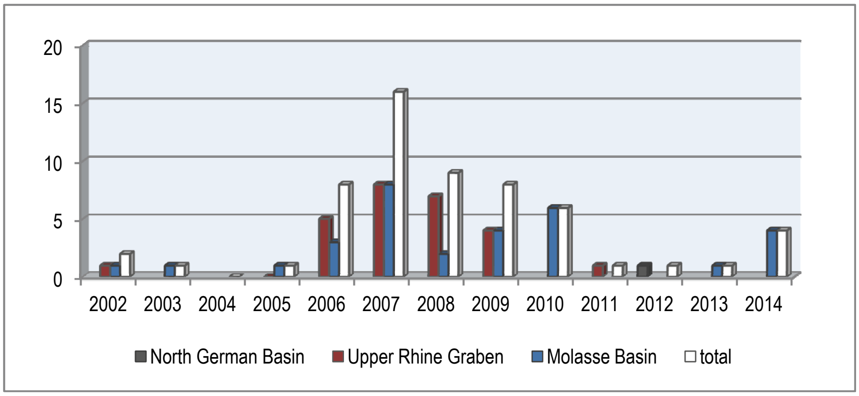

Fig. 2. Number of expert studies to quantify the exploration risk for geothermal projects grouped by geothermal region and year of completion.

For one of the evaluated wells, only hydraulic parameters were assessed and for another well only the statement for the temperature could be evaluated. Thus for the evaluation of temperature and hydraulic parameters each, data from 13 wells could be used. Most of the evaluated wells were drilled in the South German Molasse Basin.

3. Quantification of the exploration risk

The method used to quantify the exploration risk was described in detail several articles [4, 5, 6, 7] and is only shortly summarized here.

3.1. Exploration risk

The exploration risk concerning geothermal wells is the risk of not successfully achieving economically acceptable minimum levels of thermal water production (minimum flow rates for a given drawdown) and reservoir temperatures [8]. This can also be expressed as the risk of not encountering a geothermal reservoir with sufficient quantity or quality by one (or more) well(s) [4]. Quality here means the fluid chemistry, which can impede a technical use. The decisive factor is the quantity or thermal power of a geothermal well which can be calculated as:

$$P = \rho_F \cdot c_F \cdot Q \cdot (T_i - T_o) \tag{1}$$

with P power [W], ρ_F fluid density [kg m^{-3}], c_F specific heat capacity [J kg^{-1} K^{-1}], Q flow rate [m³ s^{-1}], T_i input temperature [K], T_o output temperature [K]. The achievable power mainly depends on the flow rate and the fluid temperature at the wellhead (or input temperature T_i). The output temperature T_o is the fluid temperature after heat withdrawal in the aboveground heat exchanger. It depends on technical and economical factors.

3.2. Probability of success

For long production times and high flow rates common for geothermal wells, it can be assumed that the wellhead temperature approximates the aquifer temperature; the difference then is negligible. The thermal power can thus be related directly to flow rate and aquifer temperature [4]. As discharge and aquifer temperature are independent and can be measured separately, the risk for each parameter can be determined individually. To calculate the probability of success (POS) for a planned well, the individual risks for temperature and flow rate were determined first. The overall probability was then calculated as the product of the individual probabilities [4]:

$$p = p_1 \cdot p_2 \tag{2}$$

with p being the probability of success, and p_1 and p_2 the individual probabilities for flow rate and temperature.

According to the definition, the exploration risk is defined by not reaching an economically acceptable flow rate and/ or temperature. Thus a geothermal well can be considered successful, if the achieved flow rate and temperature (or rather their product) meet the economic requirements. Considering the expert reports, economic requirements varied individually from project to project depending on the intended use and other factors. The necessary parameters were usually derived from the business plan and were thus individually determined for each project by the project management.

3.3. Calculation of the probability of success for a given temperature

Data base for the temperature assessment was the Geophysics Information System [9] which contains temperature information for the subsurface from about 11,000 wells in Germany. To determine the prospect for a given temperature, data from the surroundings of the planned well location was used, usually covering an area of about 1,200 km² or larger if local data was too sparse for an assessment. In general, the number of temperature measurements in depths interesting for geothermal uses was not sufficient to determine the temperature prospect, thus the temperature had to be extrapolated to the reference depth with the temperature gradient from shallower wells in the surroundings of the planned well by:

$$T(z) = T_0 + z \cdot grad\ T \qquad (3)$$

T_0 mean surface temperature [°C]
$T(z)$ temperature in depth z [°C]
z depth [km]
$grad\ T$ temperature gradient [K/km]

In highly productive aquifers, which are the primary target for geothermal exploration, the intense vertical mixing of the water effects that no significant increase of the temperature occurs within the aquifer [5]. Therefore, the top of the aquifer was used as reference point for the temperature assessment in the expert reports. To calculate the probability of success (POS) for a given (minimum) temperature $T(t)$ at the top of the aquifer, local temperature information was used and extrapolated to the target depth $T(z)$ (Eq. 3). In earlier studies, the probability of success was calculated as the proportion of wells reaching the given temperature in the reference depth [6]. Since 2008, the distance to the planned well location was considered by an inverse distance weighing factor of $1/R^2$ [4]:

$$POS = \frac{\sum \frac{a_i}{R_i^2}}{\sum \frac{1}{R_i^2}} \qquad (4)$$

a_i "success value": $a = 1$ if $T(z) > T(t)$; $a = 0$ if $T(z) < T(t)$
R_i distance between well with temperature measurement and planned well [km]

Temperature information for greater depths in the Rhine valley was only sparse. Because of the deficiencies in the data base the temperature prospect here in some expert reports was only roughly classified.

3.4. Probability of success for hydraulic parameters

Information on the achievable flow rate is only significant together with the corresponding drawdown of the water table at-rest. To determine the probability of success for hydraulic parameters, the theoretical drawdown at a given flow rate was calculated for existing wells using regional hydraulic test data for the respective aquifer. Step-drawdown tests provided the best available data. For many wells, only one value for flow rate and corresponding drawdown was available, however. With respect to the different geological settings and data availability, different approaches were used to quantify the probability of success for the flow rate in the Rhine valley and the Molasse Basin. The respective methods are described shortly below, for details see [4, 7].

The up to 600 m thick karstified Upper Jurassic (Malm) carbonates in the subsurface of the South German Molasse Basin provide a highly productive aquifer suitable for hydrothermal uses. Besides reef areas (massive limestone facies), which are particularly susceptible for karstification and dolomitisation [10], fault zones as possible water paths are in the focus of geothermal exploration [11]. An assessment of the probability of success for hydraulic parameters is difficult, because the Malm carbonates show an extremely high local variability typical for a karst aquifer; even the productivity of nearby wells can differ by more than factor 10 [12].

However, regional trends of the hydraulic conductivity are known, which should be taken into account [12]. Statements about the hydraulic conductivity of the Malm aquifer are therefore mainly reasonable on a regional scale. Using regional pump test data from the Malm aquifer, the theoretical drawdown was calculated for a predetermined flow rate for each well. The data base has increased significantly from 16 values for flow rate and drawdown available for the first report in 2003 to presently 82 values. For the Malm aquifer, Birner et al. (2007) [13] collected and evaluated pump test data from the Bavarian part of the Molasse Basin. In 2014, the data base was updated with data from nearly all new geothermal projects with the help of project operators.
Geothermal wells usually operate within a turbulent regime whereas the flow within the aquifer is assumed to be laminar [14]. A mixed laminar-turbulent flow was assumed as the relevant case for the assessment, however the pressure drop was also calculated for a laminar and fully turbulent flow regime. For laminar-turbulent flow, the expected pressure drop Δp_e [MPa] for the given flow rate Q' [m³/s] was calculated from the measured values for flow rate and pressure drop Q [m³/s] and Δp [MPa] as follows [4]:

$$\Delta p_e = a' \cdot Q' + a' \cdot \frac{b}{a} \cdot Q'^2 \qquad \text{with} \qquad a' = \frac{\Delta p}{Q + \frac{b}{a} \cdot Q^2} \tag{5, 6}$$

The coefficients a [s/m²] and b [s²/m⁵] were determined from step-drawdown tests in existing geothermal wells. The probability of success (POS) was then calculated as the weighted proportion of wells which theoretically reached the given flow rate without exceeding the maximum allowed drawdown (Eq. 7). In the equation, a higher weight was put on geothermal wells, furthermore regional aspects were considered with a weight factor:

$$POS = \frac{\sum u_i w_i \cdot a_i}{\sum u_i w_i} \tag{7}$$

a_i 1 for successful wells, otherwise 0
u_i weight factor for use, $u_i > 1$ for geothermal (usually 2), other uses: $u_i = 1$
w_i regional weight: $w_i > 1$ (usually 2) for nearby wells, otherwise 1
$\sum$ sum $i = 1... N$ (number of wells included in the calculation)

Main exploration targets for geothermal projects in the Upper Rhine Graben were primarily the Upper Muschelkalk and Bunter formations and deep reaching fault zones [15, 16]. Due to the available data, transmissibility values were used for the assessment of hydraulic parameters. Transmissibility values provide information about the hydraulic conductivity of a geologic layer, a cleft or a fault zone or a combination of those. Because of the very small data base for hydraulic parameters from the target units, the probability of success, which was calculated as the unweighted proportion of wells theoretically reaching the given values, was only roughly quantified. The highest class was defined with a POS over 80 %.

3.5. Seismic exploration

Information about geologic units and structures of interest for geothermal projects usually is obtained by seismic measurements. The evaluation of the results of seismic measurements was an integral part of the expert reports, especially concerning the reliability of the determination of the depth of top aquifer as reference point for the temperature assessment and the identification of possible target structures [5]. In geothermal project planning, seismic exploration focuses on the identification of structures which promise a higher hydraulic conductivity, such as fault zones or favorable facies areas [15]. The first planned projects which were assessed in the early 2000s, mainly used seismic profiles from hydrocarbon exploration. Seismic data was reprocessed and newly interpreted regarding possible targets for geothermal use [5]. In the following years, some projects were planned based on own 2D lines, but since about 2007 the use of comprehensive 3D seismic surveys has increasingly become standard practice [17]. Most of the projects which used 3D seismics are still in the planning, so too little information is available to judge to what extent a detailed seismic exploration will contribute to a mitigation of the exploration risk.

4. Evaluation of the temperature assessments

4.1. Data and method

For geothermal projects in the Molasse Basin, 22 expert studies including temperature assessment for 15 planned locations were carried out (several projects ordered more than one study). At nine previously examined locations, drilling was completed in the meantime. Data from the first well of each project was used for the evaluation. In the Upper Rhine Graben, 25 reports for 15 planned projects sites were completed; however, to date wells were drilled only at four sites. Altogether, data from 13 wells was available for the evaluation of temperature assessments in the Molasse Basin and the Upper Rhine Graben.

The evaluation of the temperature assessments was carried out individually for each examined well site taking into account available data at the time the reports were carried out, quality of seismic exploration and predicted and actual depth of top aquifer. In the expert reports, the probability of success (POS) for a predefined temperature at top aquifer was stated in the form of “The POS to reach 110 °C in a depth of 4,000 m is 80 %”. Given the positive prospect to reach a minimum temperature of 110 °C, this statement would have been evaluated as correct if 110 °C or more was reached, though the statement also contains a risk of 20 %.

Additionally, the probability for the measured temperature of a well was assessed based on the data used for the expert reports. This retrospective assessment served to check the reliability of the methodical approach and as decision guidance when stated probabilities were rather moderate and allowed no clear evaluation. 50 % ± 10 % was assumed a reasonable probability for the measured temperature. To visualize the findings, assessed temperature and actual temperature of the examined wells were added to a plot of the probability distribution of the temperature based on Eq. (4) (Fig. 3). Plots of the probability distribution were included in newer studies but had to be reconstructed for all evaluated wells based on the data set available for the expert report.

If the POS was assessed for several temperature values within the same study, the minimum value was used as the criterion for the evaluation. In case more than one report was carried out for the same project, the last report was relevant for the evaluation, as it was based on the newest data and the most up-to-date exploration target.

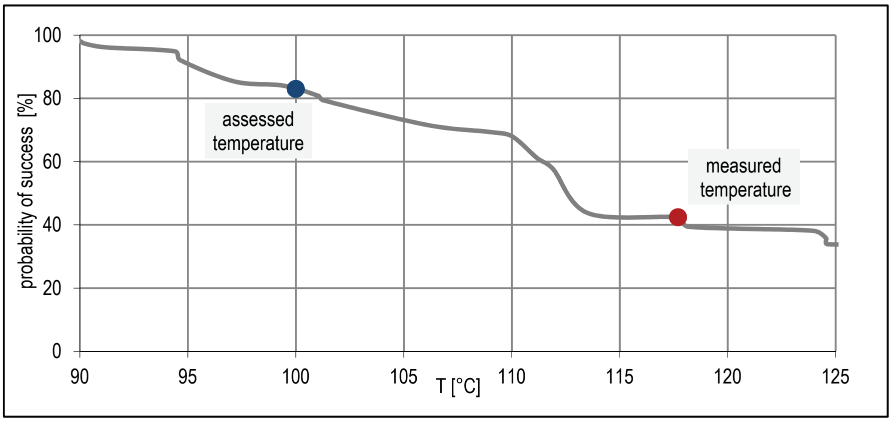

Fig. 3. Probability distribution of the temperature based on Eq. (4) for a well in the South German Molasse Basin. For this assessment from an expert report from 2008, temperature data from 31 wells in a radius of 13 km around the planned location was used. Blue dot: assessed temperature; red: actually reached temperature.

4.2. Results of the evaluation of the temperature assessment

In the Molasse Basin, all nine evaluated wells reached or exceeded the minimum temperatures and thus confirmed the stated positive prospect for the predetermined temperature values. At two of these nine locations, the actual temperature was higher than expected: Though the high probabilities to reach the minimum temperatures applied, only low probabilities would have been stated in retrospect for the measured temperatures using Eq. (4) and the data base available at the time the studies were carried out. For these two wells, the assessment of the temperature prospect was thus considered too conservative. As the high probabilities for the assessed temperatures were confirmed and the higher temperatures were positive for the projects, the assessments were still valuable as a basis for insurance contracts.

The small data base for the evaluation of wells in the Upper Rhine Graben showed a heterogeneous result. At three evaluated well locations, the temperature prospect was assessed correctly. The measured temperature in another well was 7 °C below the minimum value of 155 °C in 3 km depth for which a probability or 80 % was stated. Though this also means a risk of 20 %, the statement here was evaluated as too positive.

4.3. Evaluation of top aquifer as reference point

In highly productive aquifers the vertical mixing of the thermal water leads to a decline of the geothermal gradient often to almost zero, whereas this does not apply if a well only accesses geologic units of minor permeability. Typical temperature profiles from successful geothermal wells often do not show any significant increase of the temperature over the aquifer thickness (Fig. 4). For the assessment of the temperature prospect, top aquifer was therefore used as reference point. As an increase of the temperature within the aquifer is still possible, the determination of top aquifer as reference point leads to a conservative estimate of the water temperature [4].

Evaluating the expert reports one question to be answered was, if this conservative approach resulted in a systematic underestimation of the temperature. An analysis of 20 temperature logs from geothermal wells in Germany showed that if a well accessed layers of high permeability, the temperature depth diagrams always showed a significant decrease in the temperature gradient when reaching the aquifer (see Fig. 4). This indicates that the determination of top aquifer as reference point was reasonable. A systematic underestimation of the temperature could not be determined.

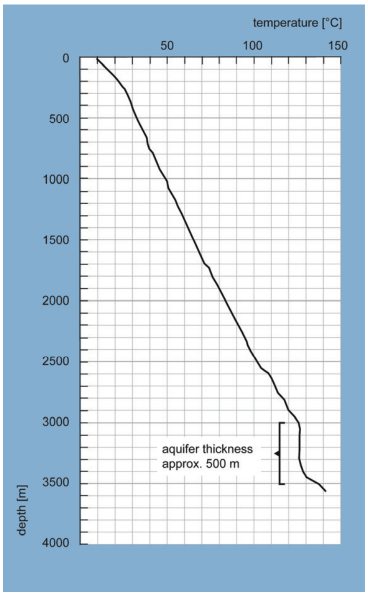

Fig. 4. Temperature depth diagram of a geothermal well in the South German Molasse Basin based on a continuous log (Geophysics Information System [9] www.fis-geophysik.de; data excerpt 12 March 2015, adapted). The karstified Malm limestone, target of geothermal exploration, was reached in about 3,000 m depth. Top Malm can easily be identified by the sudden drop of the temperature gradient to nearly zero.

5. Evaluation of the prospect for the flow rate

5.1. Data and method

For the evaluation of the assessment of hydraulic parameters, data from a total of 13 wells was available, ten situated in the Molasse Basin and three in the Upper Rhine Graben. One of the examined wells in the Molasse Basin was not drilled according to the initial concept; therefore, a statement for this well was only possible to a limited extent. Due to a different geology and different approaches to calculate the exploration risk (see 3.4), the evaluation of the stated probabilities to reach a given flow rate at a maximum allowed drawdown was carried out separately for wells in the Molasse Basin and the Upper Rhine Graben. Based on economic considerations, the clients defined the values for a minimum flow rate at a maximum allowed drawdown of the water table at-rest. As an example, the POS was calculated as the probability of reaching a minimum flow rate of 80 l/s at a maximum drawdown of the water table of 300 m, which corresponds to a maximum pressure drop Δp of 2.94 MPa or 29.4 bar, respectively.

Predetermined flow rate and actually reached discharge were often not directly comparable due to varying pump test rates. Therefore, the specific capacity or productivity index (*PI*) was used to compare the stated probabilities of the minimum parameters with actual pump test data. The *PI* [m³ s^{-1} MPa^{-1}] is the ratio of flow rate Q [m³/s] and corresponding drawdown s [m water column] of the water table or of the pressure drop Δp [MPa]:

$$PI = \frac{Q}{\Delta p} \tag{8}$$

The PI is not constant but decreases with growing discharge mainly due to an increasingly turbulent inflow [14]. To compare the given PI with the actual PI at a defined flow rate, the measured PI was extrapolated to the particular flow rate using the individual drawdown curves of each well when possible.

For projects in the Rhine valley, transmissibility data was used to calculate the POS. To compare the minimum requirements with transmissibility data from pump tests, the productivity index was used to calculate a resulting minimum transmissibility by:

$$T = \mu \cdot PI \tag{9}$$

with T transmissibility [m³], μ fluid viscosity [Pa · s], and *PI* productivity index [m³ s^{-1} MPa^{-1}].

If the POS was assessed for several $Q/\Delta p$ combinations within the same report, the minimum requirements were used as the criterion of success. In case more than one report was carried out for the same project, only the last was used for the evaluation. Newer reports also contained a diagram of the probability distribution of the theoretical drawdown at a given flow rate assuming laminar-turbulent flow. These diagrams were reconstructed for all evaluated wells in the Molasse Basin based on the former data sets (Fig. 5). To illustrate the probabilities of assessed and actually reached values, these values were added to the diagram.

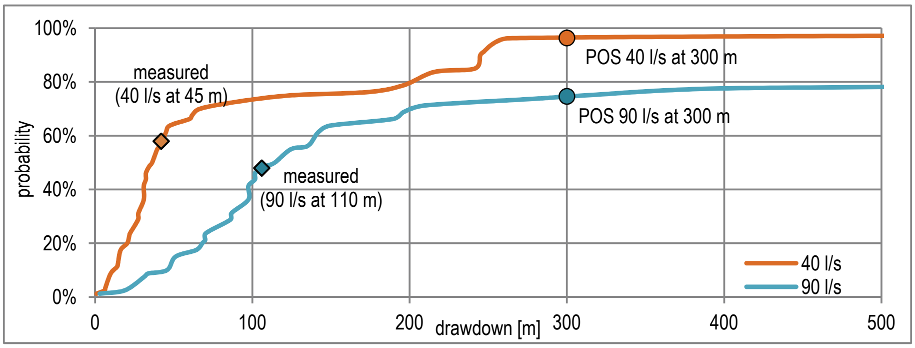

Fig. 5. Probability distribution of the theoretical drawdown for given flow rates of 40 l/s and 90 l/s for the Malm aquifer (Eq. 7). Curves based on data from 2007 (37 values). Circles: assessed values and probability, squares: measured values.

5.2. Results of the evaluation of the stated probabilities for hydraulic parameters

The prospect to reach the minimum values was stated positively for all examined wells in the South German Molasse Basin. From ten evaluated wells in the Molasse Basin, eight reached or exceeded the minimum flow rate and confirmed the stated high probabilities. Two wells failed the target minimum productivity, in these cases the assessment was too optimistic and not correct. However, one of these wells did not target a fault zone as in intended in the initial drilling concept, the respective report was therefore only of limited use for the evaluation.

In the Upper Rhine Graben, only three wells could be used for a comparison of stated probabilities and actual hydraulic parameters. One of these wells was a failure, but the probability to reach the given values was clearly below 50 %; thus the assessment in the export report was correct. The prospect for the hydraulic productivity was positively assessed for the other two wells which proved to be successful and thus confirmed the assessment.

5.3. Theoretical drawdown and weight factors

To check the reliability of the calculation of the theoretical drawdown for the laminar-turbulent flow regime (Eq. 5 and 6), the theoretical drawdown was compared to the actual drawdown derived from new step-drawdown tests. The comparison indicated that the calculation of the theoretical drawdown brought reasonable results and confirmed the assumption of laminar-turbulent flow as the most probable case.

Considering the weight factors, it seemed reasonable to put a higher weight on geothermal wells compared to other uses, as they often differ from other wells by long deviation paths in the reservoir, large diameters and engineering or acidizing measures [14]. Chosen regional weights did not significantly affect the probabilities.

6. Discussion

The prospect to reach a given minimum temperature was correctly stated for 12 of 13 wells. At two sites, the temperature was underestimated. Though the probabilities for the minimum values were confirmed, higher temperatures were only expected with low probability. One report gave a too optimistic assessment of the temperature prospect. The quality of the statements was especially influenced by data availability, data distribution, and data quality. A disadvantage of the frequently used inverse distance weighting was the overvaluation of nearby wells. Considering the often only sparse temperature information, the expert reports provided a detailed analysis of the local temperature field and reasonable assessments of the probabilities for given temperature values.

Though the determination of top aquifer as reference point gave a conservative estimate of the temperature, it did not result in a systematic underestimation of the temperature and proved to be a reasonable target for temperature assessments. A significant underestimation of the production temperature resulting from the chosen target depth is unlikely and it is recommended to keep top aquifer as reference depth for future temperature assessments.

Probabilities for predetermined flow rates and drawdown were stated correctly for 11 of 13 examined wells, though strictly speaking one of the incorrectly judged wells has to be excluded from the consideration as it was not drilled to the initial concept. Compared with actual drawdown values derived from step-drawdown tests, the approach to calculate the theoretical drawdown resulted in a reasonable approximation of the drawdown. This calculation was necessary, as the quality of most of the earlier data specifications did not allow to derive the individual drawdown for the wells. In some cases, high quality step-drawdown data from new geothermal wells allowed to replace the theoretical drawdown by the individual drawdown equation. A revision of used weight factors for the Malm aquifer should take into account regional tendencies of hydraulic properties [12], while the higher weight for geothermal wells compared to other uses seemed reasonable.

The quantification of the exploration risk did not take into account local geologic features, drilling targets, or results of the seismic exploration. Valid information on fault zones or intersected facies areas was not available for all wells and thus could not be considered in a quantitative way. The expert reports included a qualitative evaluation of seismic data, especially concerning the depth of top aquifer and possible targets. The comprehensive 3D seismic exploration meanwhile common for geothermal projects [17] was attached more importance in most recent reports by including a separate chapter for a detailed valuation of the results of the seismic exploration and the reliability of the interpretation.

7. Conclusions

Despite the small data base, this work shows that the method for the assessment of the exploration risk applied in expert reports for geothermal projects in Germany provided reliable results. In individual cases, the prospects to reach economically acceptable parameters for the wells were judged too high or too low, but no systematic error within the methodical approach could be found. Therefore, it can be concluded that incorrect assessments of the exploration risk are due to the inherent uncertainties of the geology and can only be avoided by improving the data base for the analyses. The expert reports were written with the intent to obtain an insurance coverage. Given the fact that this requires a balance of interests - the insured values for temperature and specific capacity have to be high enough to be economical but low enough to result in a low risk -, the expert reports fulfilled the expectations in the clear majority of the cases and gave reliable estimates of the exploration risk.

The results of this evaluation serve as a basis for a further development of the methodical approach, which should take into consideration an improved data base, regional variations of the hydraulic conductivity and local features, as well as the intensified use of 3D seismics for geothermal projects, which is expected to further mitigate the exploration risk.

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