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TOWARDS A BEST PRACTICE METHODOLOGICAL APPRAISAL SYSTEM FOR DEEP GEOTHERMAL ENERGY SYSTEMS IN AQUIFERS

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ABSTRACT

Pursuit and use of geothermal energy in the Netherlands is developing steadily. However, in order to make sound decisions, investors and insurers are requesting the probability of success of each planned geothermal project. A methodological appraisal system was developed in order to achieve a meaningful probability of success of the expected flow rate and thermal capacity. The appraisal system follows a methodological workflow integrating the errors in raw data, uncertainties in the geological interpretation, and in projected design of the geothermal system. The designed appraisal system is capable of working with all data available within sedimentary basins and comprises three major steps.

The first two steps comprise Monte Carlo simulations. In the first simulation every calculation of the petrophysical analysis, within predefined uncertainty or error bands, is redone to determine the uncertainties for all significant parameters. A sensitivity analysis has revealed that within this step a crucial parameter is the uncertainty in the derived porosity-permeability relationship.
This first step will be applied to every single well and the resulting probability distributions of permeability, net-to-gross ratio and temperature are combined with the results of the seismic interpretation and spatially extrapolated to the proposed subsurface locations of the planned geothermal wells.
A second Monte Carlo simulation provides the probability distributions of the desired variables: net reservoir thickness, reservoir temperature, reservoir depth, and transmissivity.
The third and final step delivers the information investors and insurers are actually interested in: the probability distributions of the feasible thermal capacity and the feasible flow rate, which are calculated by running the results of the second step through a simple analytical reservoir model. This reservoir model includes reservoir properties, properties of formation water, and well design. One parameter with significant influence on the feasible flow/installed thermal capacity and thus economics of the project is the coefficient of performance (COP). The COP can be adjusted within the model to meet client requirements.

Although it is realized that this model may need some refinement, in particular when it comes to spatial extrapolation of well data, it is believed that this is the best practice at the moment, yielding a solution that covers the most significant uncertainties for geothermal reservoir feasibility studies in sedimentary rock.

INTRODUCTION

With the current state of development of deep geothermal energy in the Netherlands, investors as well as insurers are requesting comprehensible information as base to their decisions. This information comprises amongst others figures preferably in units such as flow or delivered thermal or electrical capacity. In the Netherlands geothermal systems are currently being planned and realized in sedimentary aquifer systems between 1,500 and 3,000 m depth (van Heekeren and Koenders 2010).

These aquifer systems are layers of sandstone or limestone and have been targeted by the oil and gas industry for production since the 1940’s. Consequently, the Dutch subsurface has been extensively sampled by wells and seismic surveys. This dataset, consisting of thousands of well logs and tens of thousands of square kilometers 3D seismic data, is however biased on the potential oil and gas provinces. The difference between oil and gas exploration and geothermal exploration is found in the targeted subsurface structures. Where oil and gas accumulations are found in structural highs or traps, geothermal reservoirs are ideally located in deep extended structures. Consequently most available well data are restricted to structurally highs and thus potentially less valuable for geothermal exploration purposes. This bias leads to an enhanced uncertainty in quantitative geological parameters when assessing the aquifer systems for their geothermal potential.

Currently no consensus exists in the Netherlands on how to quantify the geological uncertainties when assessing geothermal feasibility. For the national geothermal guarantee fund founded by the government, an attempt has been made by TNO[1] with DoubletCalc (Mijnlieff *et al.* 2009). Doublet Calc comprises a Monte Carlo simulation to predict the expected range of geothermal power produced by the geothermal system. However, the actual quantitative uncertainty of geological parameters is left to interpreters without guidelines, leaving this crucial topic without any apparent restraints.

In this paper a description is given of a methodology aiming at quantification of uncertainties in the geological parameters and delivering a meaningful distribution of expected flow rate and expected thermal capacity for geothermal system. The developed systematic appraisal follows a methodological workflow that takes into account measurement errors of the raw data, uncertainties in the geological interpretation, and the projected design of the geothermal system. The methodological workflow was developed as an integral part of several geothermal feasibility studies over a time span of approximately two years.

This appraisal system is aiming at the development of a reporting code for geothermal systems in sedimentary aquifers in the European geothermal market similar to the one implemented within the Australian geothermal market (The Australian Geothermal Code Committee 2008). In combination with the proposal made by TNO (Mijnlieff *et al.* 2009), this appraisal system might serve as a first step towards such reporting code supported by all stakeholders involved in the European geothermal market.

The appraisal system comprises three steps, in view of the available geological data, consisting of information from oil and gas wells, seismic data and literature. Each steps handles a bigger amount of the collected and interpreted data. The first step comprises a Monte Carlo simulation of the interpreted petrophysical data of each well. Its results are extrapolated to the project location and combined with the results of the seismic interpretation. Subsequently a second Monte-Carlo simulation is run on this new dataset, resulting in a probability distribution of relevant geological parameters, such as temperature, transmissivity and net reservoir thickness. The third and final step uses an iterative process, combining the ensemble of geological parameters with the projected well design, in order to calculate the thermal capacity and the efficiency of the geothermal system.

[1] TNO: the Dutch geological service, mainly working for the government.

WORKFLOW

Individual steps of the uncertainty analysis workflow can be grouped into two major categories, quantitative uncertainty and qualitative uncertainty. Quantitative uncertainty comprises all uncertainties which can be explicitly expressed, qualitative uncertainties on the other hand include those uncertainties which are related to concepts based on geological arguments (Bond *et al.* 2007; Bond *et al.* 2008).

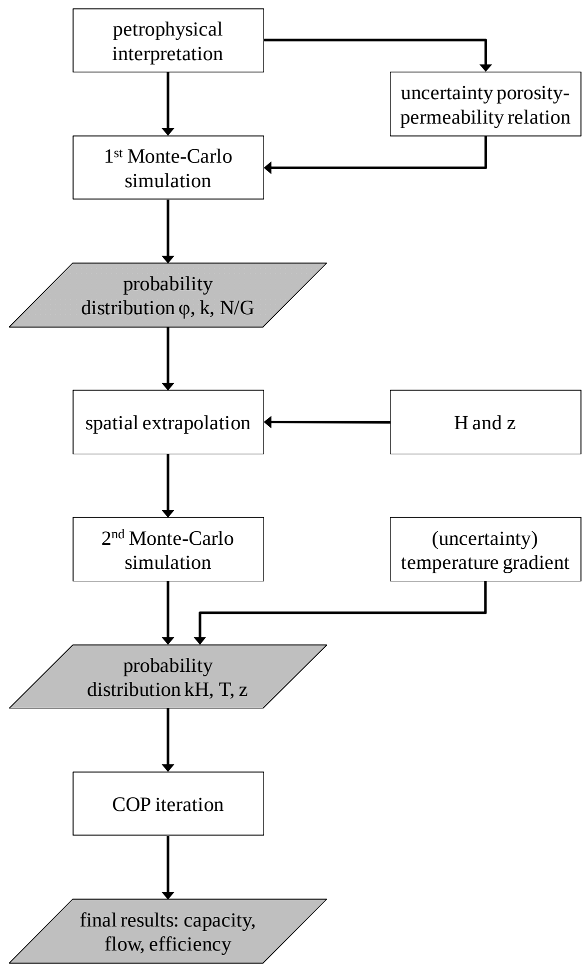


Figure 1: *Schematized flowchart of the systematic methodology described. Grey areas indicate results, rectangular white areas indicate actions. Where* φ *= porosity,* k *= permeability,* N/G *= net-to-gross ratio,* H *= gross reservoir thickness, z = reservoir depth, kH = transmissivity, and T = temperature.*

The described methodology aims at minimizing the influence of the inevitable qualitative uncertainties by quantifying as much geological parameters as possible. Nevertheless, numerous interpretative decisions based on geological insight have to be made during the analyses of well log data, resulting in qualitative information. Another qualitative point is the spatial extrapolation of the well data to the project location.

As mentioned before, the workflow is divided into three steps: a first Monte Carlo simulation and a second Monte Carlo simulation followed by a so-called 'COP iteration' to determine the thermal capacity, flow rate and efficiency of the system. In Figure 1 the flowchart of the methodology is sketched. In the following paragraphs each step shown in Figure 1 is described separately.

Step 1: first Monte Carlo simulation

For every relevant well, the available well-log data are petrophysically interpreted. This interpretation leads to a set of deterministic results such as porosity, φ, permeability, k, and net-to-gross ratio, N/G. Permeability values are estimated on basis of a porosity-permeability relation; obviously permeability constitutes a vital parameter. The uncertainty in the porosity-permeability relation significantly determines width and shape of the probability distribution of the final stochastic results.

For this purpose the uncertainty of the porosity-permeability relationship needs to be determined as accurately as possible. The porosity-permeability relationship is usually derived from a cross-plot of porosity and permeability measurements on core samples, both corrected for decompaction. A logarithmic relation is intrinsically assumed. Therefore, by plotting permeability values on a logarithmic scale, a linear relation can be found with respect to porosity values. Since the measurements are assumed to be the result of random sampling of a much bigger population, the resulting regression line will always remain an unbiased approximation of the real porosity-permeability relationship.

As measurements of both porosity and permeability are assumed to be subject to a similar degree of relative errors, the application of Reduced Major Axis (RMA) regression is preferred. Another argument in favour of the application of RMA is that the errors are uncorrelated to each other or to the quantity itself. The area of confidence is bound by hyperbole lines of 95% confidence. The asymptotes of these lines of confidence define the upper and lower values of the porosity-permeability relationship. The area of confidence of the RMA regression is approximated using a technique called bootstrapping (Bohonak 2004). In Figure 2 an example of a porosity-permeability relation with the asymptotes of its uncertainty bands is shown.

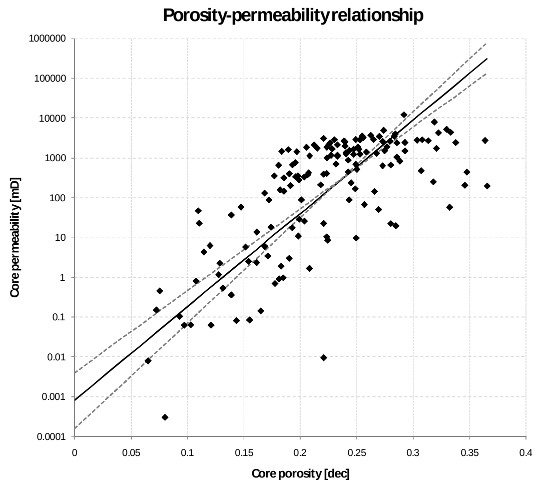


Figure 2: Example of a porosity permeability relationship. The diamonds represent individual porosity-permeability measurements. The asymptotes of the uncertainty bands are the dotted lines around the solid regression line. Note that the permeability is plotted on a logarithmic scale.

Well data form the basis of the petrophysical analysis, which are prone to measurement errors, either by instrument or more importantly by adverse borehole conditions. During the analysis itself, several sources of data are combined, leading to an accumulation of uncertainties. The range of measurement errors is well known for the logging technique; since the logs have been scrutinised for borehole effects, these errors are left out of consideration. Together with the intrinsic uncertainty in the porosity-permeability relation, the measurement errors and uncertainties are integrated into a Monte Carlo simulation. The resulting parameters that are transferred towards the next step are the probability distributions of the porosity, the permeability and the net-to-gross ratio.

It must be noted that this simulation is performed for every analysed well. This results in probability density distributions of the considered geological parameters which are valid only for the location from which they have been derived, e.g. the location of the interpreted well.

Step 2: Second Monte Carlo simulation

Since the results of the 1st Monte-Carlo simulation reflect only the geological properties at the positions of the analyzed wells, a spatial extrapolation to the projected subsurface locations of the geothermal wells has to be made. Depending on the available data, this is done quantitatively or qualitatively. At this point of the appraisal, two new parameters are added to the dataset; reservoir thickness and reservoir temperature.

Thickness

When seismic data of appropriate quality and resolution are available and reservoir thickness can be reasonably mapped, the spatial reservoir thickness and the accompanying uncertainty can be used for further analysis. It is assumed that the quality of the seismic data is sufficient to determin the depth of the reservoir. In case no appropriate seismic data are available to map reservoir thickness, the thickness measured in the well logs is used in the spatial extrapolation.

Temperature

Temperature measurements are available from wells in the form of maximum temperatures measured at the bottom of the borehole at each logging run. The measurements are taken at various time intervals between the measurement and the end of mud circulation (BHT measurements). These time intervals are generally too short for establishing a thermal equilibrium between the relative cold drilling fluid with the surrounding host rock. Therefore, the temperature measurements need to be corrected. This correction is made by applying the Horner method to the temperature data (Pasquale *et al.* 2008).

The temperature correction applies to one single depth per borehole. To find a representative geothermal gradient for a certain area, temperature measurements from different representative boreholes need to be used, resulting in a dataset of corrected temperatures and corresponding depths. The geothermal gradient is determined by applying an Ordinary Least Squares (OLS) regression to the dataset. This regression is appropriate since one of the variables, depth, can be considered free of uncertainty. Out of the regression, the uncertainty in surface temperature and geothermal gradient can easily be determined (Squires 1985; Draper and Smith 1981) and represented graphically (Figure 3).

Spatial extrapolation

A quantitative spatial extrapolation can be made by Kriging or some other extrapolation method, when sufficient representative data points are available. Qualitative spatial extrapolation is based on geological insight, experience and/or literature and can for example be performed by applying some weighting method or, when considering permeability and porosity, depth correction to the data. Local geological setting should always be taken into account, e.g. faults, depositional history and/or tectonic history, for either approach. The parameters spatially extrapolated are porosity, permeability, and net-to-gross ratio. The porosity-permeability relationship and the geothermal gradient are not tied to location and consequently do not need to be extrapolated.

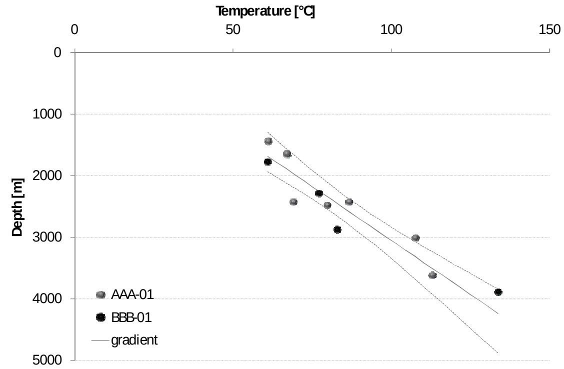
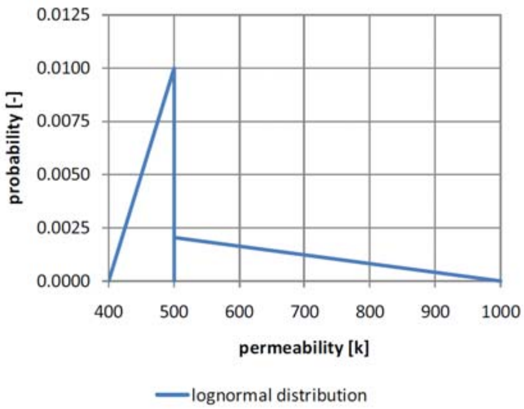


Figure 3: Example of a geothermal gradient with uncertainty bands.

Second Monte Carlo simulation

The individual values of the created probability distributions are generally expressed as p-values or percentiles, which represents the probability of a certain value to occur within the distribution. A p97.5 value for permeability of 100 mD implies that 97.5 percent of the probability distribution contains values greater than 100 mD. In other words: there is a 97.5% chance that the actual value is greater than 100 mD. A 95% confidence interval of the probability distribution of a certain parameter can be expressed with its p97.5, p50 and p2.5 values.

The p97.5, p50 and p2.5 values of the extrapolated parameters: average permeability and net-to-gross ratio as well as p97.5, p50 and p2.5 values of the gross reservoir thickness, reservoir depth, and the values of the variation in the geothermal gradient are integrated into the second Monte Carlo simulation. It is assumed that the variables considered can be approximated either by a normal (e.g. porosity) or a lognormal (e.g. permeability) probability distribution. For the Monte Carlo simulation the probability distribution of the variables are represented by a double triangle distribution approximation, given the fact that for some variables the value-range at one side of the distribution is significantly different compared to the other side. Moreover, a double triangular distribution is a better approximation to a log-normal distribution than a single-triangular one. In Figure 4 a double triangular approximation is given for both a permeability (log-normal) and a porosity (normal) distribution. The second Monte Carlo simulation results in probability distributions of reservoir temperature, transmissivity (net thickness x permeability), reservoir net thickness and reservoir depth.



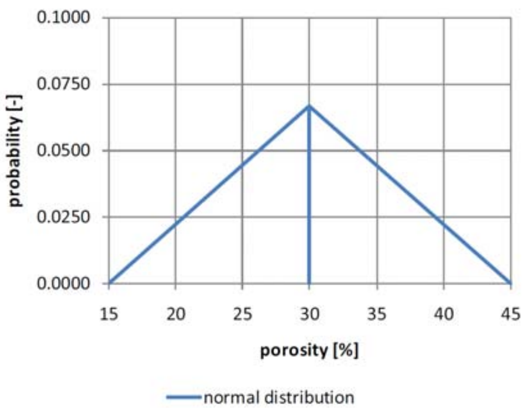


Figure 4: *Examples of a double triangular distribution approximation for both a lognormal (permeability) and a normal (porosity) distribution.*

<u>Step 3: COP iteration</u>

The Coefficient of Performance (COP) is a measure of the environmental sustainability of the geothermal system. It is the ratio between the thermal capacity installed and the capacity needed to keep the system running. Consequently a higher COP represents a higher efficiency of the geothermal system and is thus a measure of its environmental sustainability. However, in view of the need to be economically viable, investors and insurers are generally only interested in thermal capacity and the potential flow rate from the geothermal system.

The COP is determined by a large number of parameters, derived from the results of the second Monte Carlo simulation (i.e. depth, temperature and transmissivity), pressures in the reservoir, properties of the formation water, proposed well and system design and flow rate. Formation pressures and properties of the formation water are intrinsically dependent on depth and temperature of the geothermal reservoir. The well design influences both flow rate and thermal capacity and is represented by the total length of tubing of the geothermal system. The diameter of the tubing is assumed constant and equal to the narrowest tubing installed in the geothermal wells. The total produced geothermal capacity as well as the necessary pump capacity corresponding to a certain flow rate can be determined by summation of pressures developed in every component of the geothermal system. In Figure 5 a basic geothermal system with its main components, aquifer at the production well, production well, injection well and aquifer at the injection well, is sketched.

When the COP is taken as fixed value, thermal capacity and flow rate - both dependent on temperature and transmissivity - can only be determined with an iterative approach. The COP iteration combines the output values for temperature and transmissivity of the second Monte Carlo simulation to find the probability distributions of thermal capacity and flow rate for a predetermined COP value. The routine does this by stepwise increasing the flow rate for each temperature and transmissivity combination and comparing the resultant COP with its predefined value until the correct flow rate is found. The result is a large population of thermal capacities and flow rates of which probability distributions can be made. These are a measure of the probability of success for the desired flow rate and thermal capacity of the geothermal system.

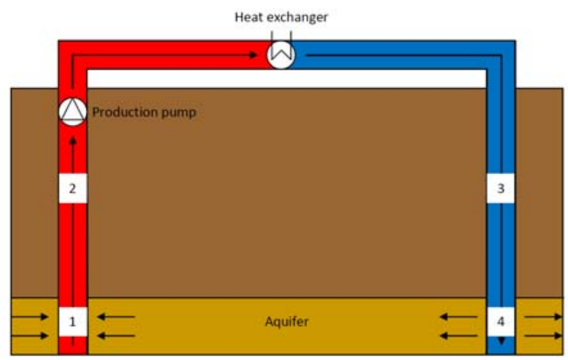


Figure 5: *Schematic sketch of a geothermal system as regarded in the COP iteration. The different components of the system regarded are: 1) aquifer at production well, 2) production well, 3) injection well, and 4) aquifer at injection well.*

<u>DISCUSSION</u>

The workflow presented in this paper is applicable for geothermal systems in sedimentary aquifers when both borehole and seismic data are available. Although some additional work is still needed for a few topics, this workflow enables quantification of uncertainties of relevant geological parameters during a geothermal project.

One of the topics that need to be further worked out is the spatial extrapolation of the results of the first Monte Carlo simulation. Since the quality of the seismic data is seldom sufficient to map reservoir thickness, qualitative spatial extrapolation is needed. Furthermore, the number of interpretably wells is limited by the lack of good quality borehole data and time constraints, often resulting in a spatial extrapolation based on only two to three interpreted wells. Sparse data sets make gridding results subject to large uncertainty and the application of a qualitative spatial extrapolation method necessary. Since qualitative spatial extrapolation is based solely on geological insight, experience and the imagination of the specialist, the spatial extrapolation is a potential weak link in the appraisal.

Potentially Kriging has the possibilities to overcome the problem of the uncertainties inherent to qualitative spatial extrapolation. However, to achieve a trustworthy spatial extrapolation by Kriging a large dataset is necessary for the construction the semivariogram, that characterises the spatial dependence. This dataset may be created by using data from a greater area or transferred from analogous sedimentary basins. The application of Kriging for quantitative extrapolation thus requires the interpretation of additional data. A potential drawback from applying this gridding routine is that by increasing the dataset, the resulting spatial extrapolation becomes more regional and is thus less representative for the project location.

Another point that is not taken into account in the uncertainty analysis, is the relation between depth and porosity (Athy 1930; Dutta 2002). This can lead to inaccuracies when large depth differences exist between the geothermal reservoir at the project location and the location of the interpreted wells. The depth correction should be applied on the porosity distribution after the porosity is spatially extrapolated, it can also be applied to the porosity distribution representative for the reservoir, but only when the standard deviation of the distribution is corrected simultaneously. To integrate the depth correction properly the developed routines are currently being adjusted.

Currently only the uncertainties in transmissivity and temperature are taken into account when calculating the feasible flow rate and thermal capacity. The uncertainty in the depth however is not regarded when running the COP iteration. Since the properties of the formation water are solely dependent on depth the uncertainty in depth should also be integrated into the COP iteration routine. In actual fact, properties of the formation water as well as the tubing length are functions of reservoir depth. Consequently, uncertainty in reservoir depth has a dual impact on flow rate and capacity. This was realized by the developers of DoubletCalc and recently routines were adapted, honoring this fact.

The Horner plot method used to correct temperature at depth is just one of several available methods to correct BHT measurements. Although more accurate methods might be available (Hermanrud 1990) the Horner plot method is widely used and generally accepted as a good method to approximate the temperature at depth.

The dip of the layers in a geothermal reservoir is generally low (<10°) and only lateral horizontal extrapolation is sufficient when spatial extrapolating. However, when the dip of the layers is relatively large the difference between the lateral horizontal distance and the actual distance between the spatially extrapolated well and the project location becomes significant by geometry. For large dips a depth dimension is also required for spatial extrapolation. For extrapolation in the depth dimension a 3D structural model of the reservoir is needed. In reality these large dips are however rare when interpreting wells with respect to geothermal reservoirs.

CONCLUSIONS

The presented workflow delivers an elegant methodology to quantify uncertainties in the most relevant geological parameters when assessing the feasibility of a geothermal project in a sedimentary aquifer system. The methodology follows three major steps:

- Step 1: 1st Monte Carlo simulation which determines the probability distributions of porosity, permeability and net-to-gross ratio of the reservoir in a borehole.
- Step 2: 2nd Monte Carlo simulation that delivers the probability distributions of net reservoir thickness, transmissivity, temperature and reservoir depth for the projected subsurface location of the geothermal wells.
- Step 3: A COP iteration resulting in the probability distribution of the thermal capacity and the flow rate of the geothermal system.

Several topics need some additional work, the two most important being the development of a structural methodology for the qualitative spatial extrapolation and the integration of a methodology for the depth correction of the porosity.

In the future the workflow might be expanded with input parameters from for example the results from applying acoustic impedance to the seismic data or the results from a basin analysis and/or other results from additional studies.

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