Uncertainty analysis of groundwater flow impacts on the performance of a BHE array

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Introduction

Shallow geothermal energy has been popularly used for house heating and cooling by combining borehole heat exchangers (BHEs) with a heat pump. The efficiency and sustainability of BHE systems are receiving increasing attention in recent years. Groundwater flow, among the hydrogeothermal properties of the subsurface, is considered to be a critical positive factor in maintaining BHE efficiency, especially when the groundwater flux is higher than 10^{-7} m/s. However, in practice, exact information on local groundwater flow is typically not available. Rough estimates may introduce significant uncertainty in the design and performance of BHE systems. In this study, we performed an uncertainty analysis of groundwater flow impacts on the system performance based on a planned BHE array, including the impacts on system economic efficiency and subsurface thermal environment.

Methodology

Groundwater flow parameters, e.g. groundwater flux, flow direction, hydraulic heterogeneity, and groundwater table, can have considerable effects on soil temperature changes and heat pump efficiency. To quantify the uncertainty caused by groundwater flow, the following four steps were developed (Figure 1):

1) Parameter uncertainty: groundwater flow parameters are assumed to vary over a range of distributions based on regional background information, although local groundwater flow information is not available.
2) Stochastic modeling of the BHE system: uncertain parameters are treated as random variables in the BHE model. Temperature changes at observation points (ΔT_{obs}) and seasonal coefficient of performance for a heat pump (*SCOP*) are controlling indicators.
3) Parameter sensitivity: according to the relations between uncertain parameters and simulated results, a global parameter sensitivity can be analyzed using the variance-based Sobol method.
4) Reliability quantification: a surrogate model is first established based on sensitive parameters, and the reliability of the designed system performance parameters is quantified using Monte Carlo simulations.

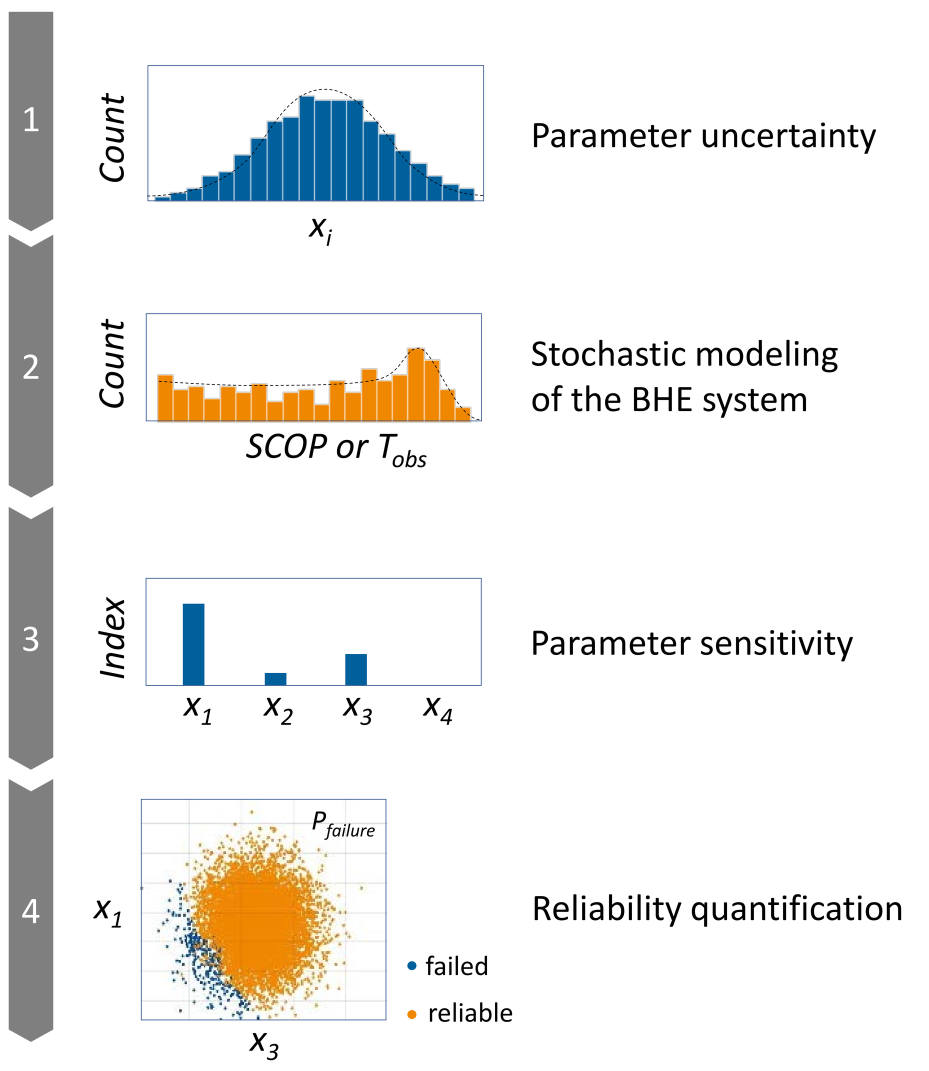

Figure 1 Main steps to quantify groundwater flow impacts on BHE system performance.

Site description

The investigation site is located in Hannover, Germany, and is planned to be constructed within the next few years. According to the design report, this site will comprise 70 BHEs, each 150 m long. To consider the effect of groundwater flow, a regional hydrogeological map and available geological data were used, as shown in Figure 2. The groundwater table depth is about 12 m, the hydraulic gradient is 0.007 and the flow direction is NNW 345°. The formation within the upper 150 m can be separated into three layers, the Darcy flux (*D*) within each layer was obtained by estimated K values.

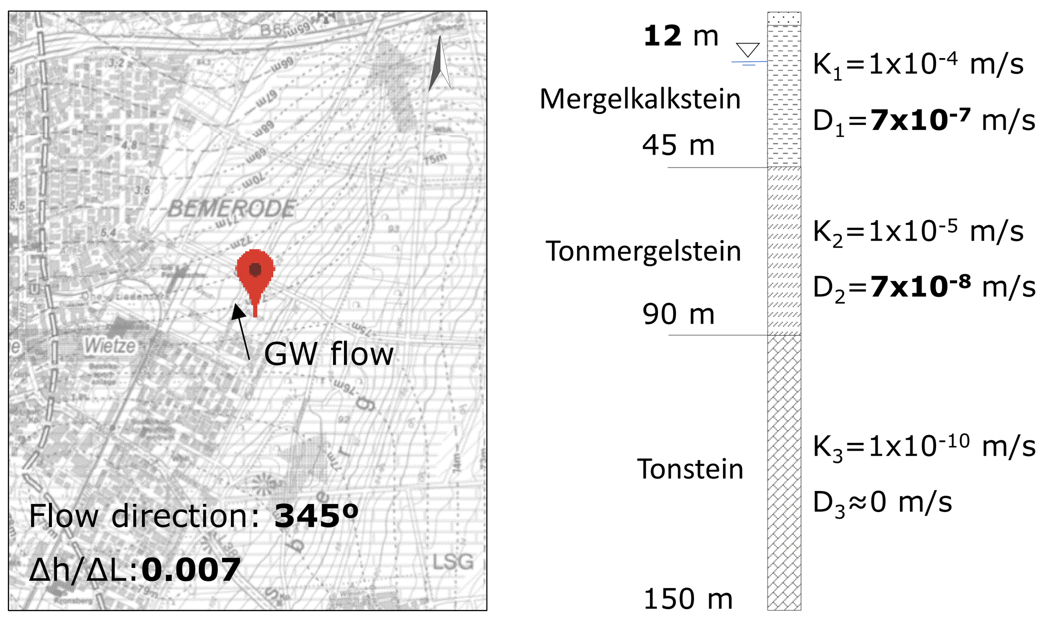

Figure 2 Hydrogeological map and typical borehole log at the Hannover site. Darcy flux in each layer is assumed.

Stochastic modeling

A Gaussian distribution is selected to describe all uncertain groundwater parameters. The mean value of each parameter is assigned by the data from regional information. Other details are listed in Table 1. A FEFLOW model coupling heat transfer in BHEs and aquifers is developed based on the Hannover site setup. In stochastic modeling, 250 realizations are considered. The arrangement of the BHEs, the FEFLOW model, and simulation results are shown in Figures 3 and 4.

Table 1 Gaussian distribution of the selected groundwater flow parameters.

Parameters	PDF	Mean E	Variance σ^2
Water level [m]	Gaussian	12	10
$\log_{10}(D_1)$ [m/s]	Gaussian	-6.16	1
$\log_{10}(D_2)$ [m/s]	Gaussian	-7.16	1
Flow direction [°]	Gaussian	345	30

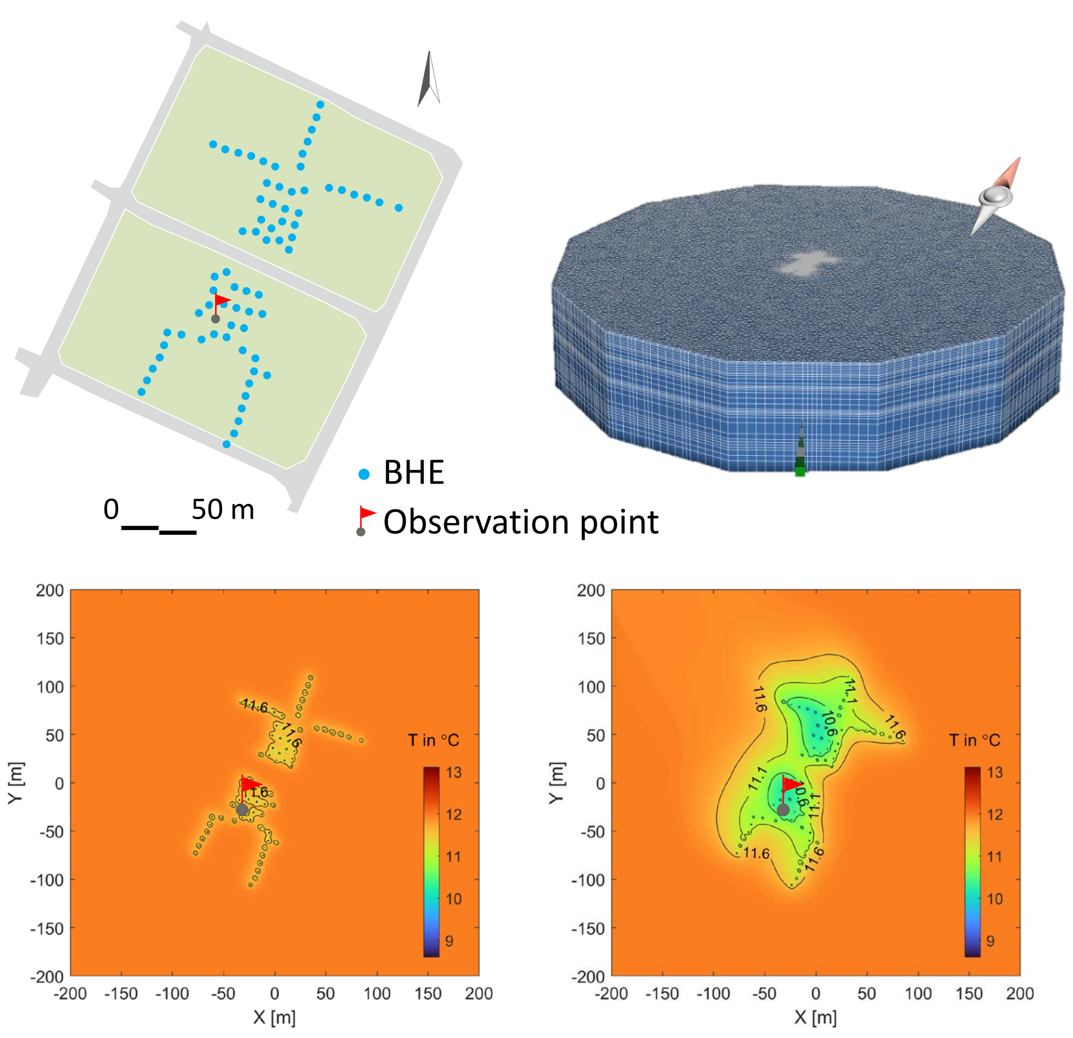

Figure 3 Arrangement of BHEs and 3D FEFLOW model (top), and simulated temperature maps in the 1st and 10th year for a parameter realization (bottom).

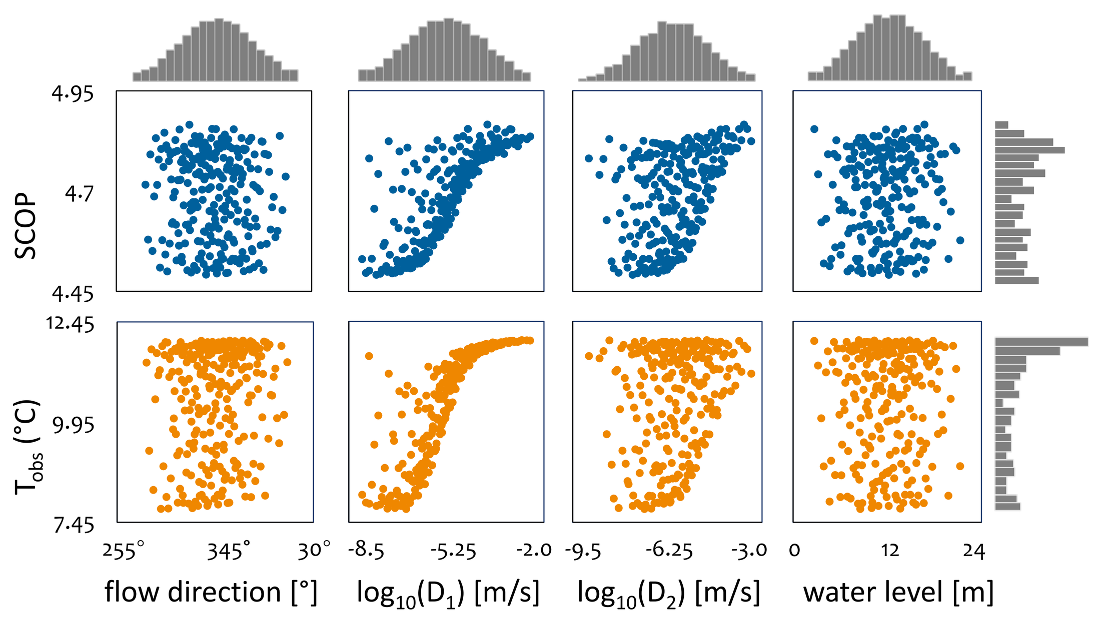

Figure 4 Simulated *SCOP* and T_{obs} versus stochastic groundwater flow parameters in the 10th simulation year.

Sensitivity and reliability

Parameter sensitivity represented by the 1st order Sobol index (S_1) is analyzed and shown in Figure 5. It is indicated that, at the Hannover site, D_1 is the most sensitive parameter for the *SCOP* and temperature change ΔT_{obs}, followed by D_2, and the groundwater table and flow directions are not quite sensitive. Comparing the result between the 1st and 10th year, the importance of D_2 to the *SCOP* will slightly decrease as the system is operated. Reliability analysis is carried out for the given system technical parameters: *SCOP* > 4.5 and $|\Delta T_{obs}| <$ 4°C. Failure probability of this system can be expressed as: $P_f = P[g(x) \le 0]$, where $g(x) = \min(SCOP\text{-}4.5, -|\Delta T_{obs}| + 4°C)$. Figure 6 depicts the P_f by surrogate model-based Monte Carlo simulations (10^5 times). Results show that the reliability of the system can reach 0.964.

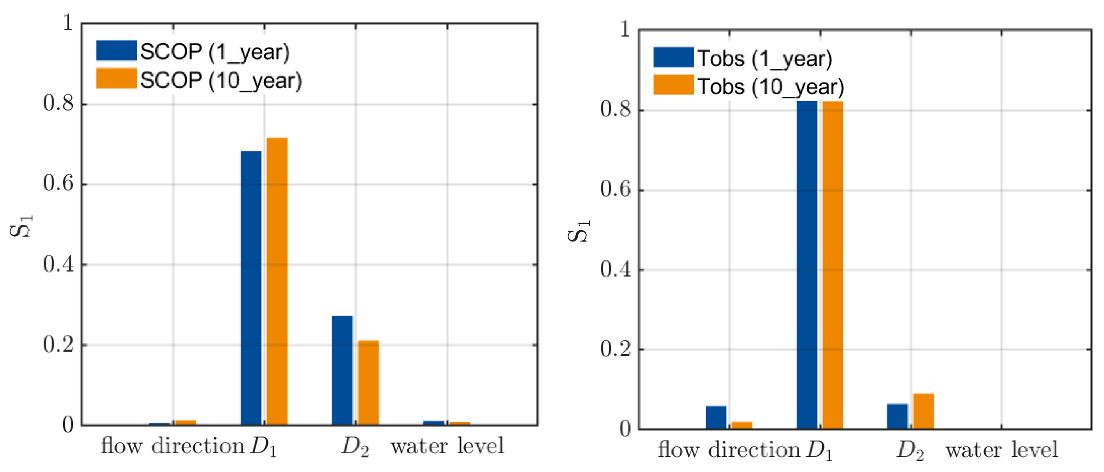

Figure 5 The 1st order Sobol indices for the *SCOP* and ΔT_{obs} in the 1st and 10th simulation year.

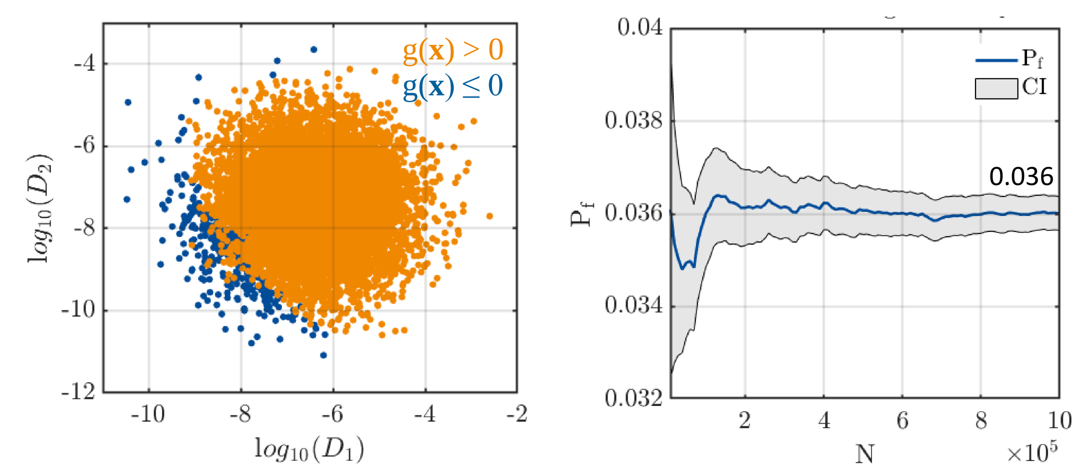

Figure 6 Scatter plot of failed ($g(x) \le 0$) and reliable ($g(x) > 0$) cases between D_1 and D_2, and the convergence of P_f, including the 95% confidence interval.

Conclusions

Following the developed methodology, we analyzed the uncertainty of BHE system performance caused by uncertain groundwater flow parameters. It can be concluded that,

1) the *SCOP* and ΔT_{obs} at the investigated site are most sensitive to groundwater flux of the 1st and 2nd layers, and almost insensitive to groundwater table and flow direction.
2) For the given system technical parameters: *SCOP* > 4.5 and $|\Delta T_{obs}| <$ 4°C, the failure probability at the investigated site is only 0.036, considering the uncertain groundwater flow parameters.

This study may provide a reference for the optimal design of BHE systems, especially in the case of high groundwater flux sites.

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