Numerical Model for the Capacity Evaluation of Shallow Groundwater Heat Pumps in Beijing Plain, China

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Abstract

The groundwater heat pump (GWHP) system utilizes groundwater as alternative renewable and clean energy source for space heating and cooling, which is an open-loop system that withdraws water from a production well, passes it through a heat exchanger and discharges the water into an injection well. By utilizing the relatively stable temperature of groundwater, GWHP system can work with a higher coefficient of performance. It is necessary to evaluate the aquifer capacity for the proper design and application of GWHP. In this paper, a numerical method of underground heat transfer, energy balance method and thermal storage method were presented to calculate the load capacity of a unit area of shallow aquifer. The model results indicate that the numerical method, which is based on performance efficiency of groundwater heat pump, reflects the behavior of groundwater pumping and recharging processes, and better than energy balance method and thermal storage method, additionally it has the advantages of energy saving and environmental protect. The capacity is positively related to aquifer thickness. The final results show that it is easy for ground water recharging in alluvial and pluvial fan located at the piedmont, while load capacity is relatively smaller. In contrast, it is difficult for groundwater recharging in south-east plain where a larger load capacity is obtained.

Key words: Groundwater heat pumps, numerical model, load capacity, energy balance method, thermal storage method

1. Introduction

Geothermal or ground source heat pumps (GSHP), as a relatively new technology, can save more homeowner money. These ground-source heat pumps use the natural heat storage capacity of the earth or ground water to provide energy efficient heating and cooling, its market penetration is significantly rapid in Europe and America. It is reported that 400GWh heat was supplied by heat pumps in 2000 in Swedish. Groundwater heat pump system, as an operating mode of GSHP, are being used widely in China,
particularly in the north area, involved in office building, commercial buildings and residential area. Groundwater heat pump realizes heat transfer between groundwater and buildings through groundwater pumping/rejection cycle and compressor, and allows building to keep warm in winter and cold in summer. GSHP developed concept takes advantages of moderate and relatively constant groundwater temperature (13°C–16°C), an ideal energy medium. Heat pump utilizes renewable and clean energy with the advantage of energy saving and environmental protection. However, groundwater resource is wasted due to the clog of injection well in some part of system during the operation, on the other hand a too small borehole distance and serious “thermal breakthrough” will result in decrease of COP (Coefficient of Performance), which requires a large amount of electricity to realize heat transfer (Sanner et al., 2003); excessive imbalanced heating/cooling demanded during the year leads to an annual temperature change within the pumping/rejecting field, which is unfavorable for long-term performance (Drijver et al., 2001). In addition, the interference among pumping/rejecting wells between neighbouring heat pumps will lower the overall performance efficiency. The buffering and renewable potential is great, but with a slow renewable process, in view of the limited area of local heat pump field, a high recharge rate, enough distance between pumping wells and the annual thermal balance in the buildings are required to allow heat pump system to work properly and energy to be renewed rapidly. In order to operate groundwater heat pumps scientifically and objectively, and avoid negative effects as well as unstable and unsustainable factors, a hydrogeological preliminary study is always necessary to carry out quantitative assessment of groundwater heat pumps application.

2. Hydrological conditions and divisions of the study domain

Beijing city is surrounded by mountains and connected with North China Plain in south-east. Quaternary structure consists of single layer contained coarse sand and gravel in piedmont and transits to superimposed multilayer structure interaction with gravel layer, sand and silty clay layers. Correspondingly unconfined shallow groundwater aquifer is transformed to the confined in the plan area. Water yield property is better in alluvial and pluvial fan located in piedmont and becomes worse in south-east plain. Shallow groundwater, as a source of heat pumps, has the advantages of utilizing clean energy and protecting deeper groundwater resources.

The depth of pumping/rejecting well of heat pumps is limited to 100 m since shallow groundwater is not portable, on the other hand, although there are many shallow aquifers in plain area and water quality become better from above to below. However, generally shallow groundwater quality is worse compared to the deep groundwater. Taking shallow groundwater as heating/cooling source of heat pump system has the advantage of utilizing clean energy and also contributes to protect deep groundwater environment.

The quantitative features are represented by permeability and thickness for shallow aquifer. Some simplifications are required to make a uniform calculation due to the complicated formation structures. Hydrological data illustrates that there are good hydraulic connections and small water level difference (<5m) between shallow aquifers. Therefore, the aquifers within 100 m can be considered as a single aquifer, also an equivalent permeability can be estimated according to the lithology and previous pumping test data. The plain area can be divided into 22 hydrogeological subdomains according to the equivalent permeability and thickness (see Fig. 1).
Figure 1. Hydrogeological sub-domain distribution  Figure 2. Scheme of pumping/injection wells in
neighbouring of shallow groundwater of Beijing plain.

3. Capacity estimation of groundwater heat pumps

In this work, three methods, numerical method, energy equilibrium method and thermal storage
method are adopted to estimate the load capacity of groundwater heat pumps scientifically and
objectively. The distribution of pumping/rejection wells, such as the number of pumping/rejecting wells,
borehole spacing and pumping discharge, should be designed according to the energy demand of building,
which makes it rather difficult to define the load capacity of single heat pump system under specific
hydrogeological setting. For this reason, load capacity in a unit area aquifer (KW/km$^2$) is employed as
the estimation standard.
3.1 Numerical method

Considerable progress has been made in the numerical model of underground heat transfer, which is widely applied in calculating heat change of water injected into the aquifer (Zhang et al., 1997) and simulating earth temperature during the application of GSHP systems (Chiasson, 1999), but it has not been available to the application of load capacity assessment of an aquifer to heat pump systems. In this paper, FEFLOW (Finite Element subsurface FLOW system) was selected for model simulations. The FEFLOW is an interactive finite element simulation system for three-dimensional or two-dimensional, i.e. horizontal (aquifer-averaged), vertical or axi-symmetric, transient or steady-state, fluid density- coupled or linear, flow and mass, flow and heat or completely coupled thermohaline transport processes in subsurface water resources.

Taking the groundwater within 100 m as heating/cooling source can avoid deep groundwater pollution. A stable performance of a single heat pump system can ensure high performance efficiency in long term. The thermal field, induced by groundwater pumping/rejection among neighbouring pumps, are not interfered with each other, which allows an overall and long-term efficiency of many pumps.

It is worth noting that some notable differences between the stratum structure and the layout of pumping/rejection wells exist in different field. Therefore, a uniform estimation procedure should be clarified for carrying out capacity assessment in different hydrogeological settings. The estimation procedures are as follows:

1) With the equivalent permeability coefficient and thickness of different subdomain, water yield capacity with 5m drawdown is estimated using groundwater seepage numerical method.

2) Due to different distribution of pumping and rejection, water yield capacity of single well is taken as pumping/rejection flux of single heat pump system, and pumping/rejection wells is considered as one as pumping and the other as rejection.

3) Thermal transfer model is established and solved numerically with a 15-year performance period. Heating and cooling period is four months and three months respectively during the year in Beijing city. Generally the temperature difference of energy transfer between pumping/rejection wells is 7°C. A certain “lift” is allowed to ensure operating efficiency of heat pump systems under the balanced pumping/rejection. The models are run under the constraint conditions of rejection water temperature (not less than 5°C at the end of heating period and not higher than 25°C at the end of cooling period). The minimum space between pumping and rejection wells is obtained by repeating adjustments to satisfy the constraints.

4) With the solution obtained in procedure (3), the span of groundwater flow field and thermal field are acquired, afterwards the analysis of mutual interference of underground thermal field between neighbouring heat pump systems are performed.

5) Cooling/heating load capacity (unit: KW) can be calculated according to groundwater pumping/rejection flux and energy transfer temperature difference at 7°C, the ratio of cooling/heating capacity to influence area of groundwater thermal field, is loading capacity of unit area in each hydrogeological subdomain.

The numerical groundwater stable flow model can be used to estimate water yield capacity of single well with a supposed boundary 4000 m × 4000 m, where water head is set as constant. Pumping well is located at the center of the simulated domain. The discretized elements are smaller near the well and increase far away. Pump discharge is obtained by inverse calculation with a constraint of 5m drawdown. Water yield capacity is acquired through a reiterative adjusting pump discharge.

Hydrogeological parameters such as permeability coefficient, effective porosity and dispersivity, and thermodynamic parameters such as volume specific heat capacity and thermal conductivity, are derived from previous pumping tests, diffusion experiments, thermo-dynamic experiments and some references.
(Bear, 1983; Chiasson, 1999; Mands and Sanner, 2001). Generally the volume specific heat capacity of clay soil is \(2.8 \times 10^6 - 3.4 \times 10^6 \text{J/m}^3\cdot\text{°C}\) and that of sand is \(1.3 \times 10^6 - 2.0 \times 10^6 \text{J/m}^3\cdot\text{°C}\), the heat conductivity of those materials is \(1.6 - 2.8 \text{W/m}\cdot\text{°C}\). The span of hydrodynamic field under balanced pumping and rejection is negligible while operating with a moderate borehole space. Therefore, a domain with \(4000 \text{m}^2\) is still used in the model, and the model boundary is put outside the span of hydrodynamic field induced by pumping/rejection, and not affects the model results. Vertically the formation is simplified as single. The thickness of clay is the actual value under groundwater table within 100 m. Fixed water head and temperature boundary conditions were set on all four sides of the model domain, and pressure head is assigned to each node. Vertically the four sides have the same water head but different hydraulic pressure. The top and bottom are specified as zero flux and constant temperature.

A hydraulic gradient, a value of \(1\%\), is supposed at natural state, water pressure is assigned to the sides as well as top and bottom based on the flow direction. The initial groundwater temperature, \(15.0\), is derived from previous experiments. The mathematical model of coupling groundwater flow and heat can be written as:

\[
\begin{align*}
\mathbf{n} \rho_b \beta_0 \frac{\partial P}{\partial t} + \rho_c \beta_1 \frac{\partial T}{\partial t} + \rho c_b \frac{\partial P}{\partial t} = \nabla \cdot \rho \frac{K_p}{\mu} (\nabla P + \rho g) \\
\mathbf{n} \rho_b \beta_0 c_s T \frac{\partial P}{\partial t} + \rho_c \beta_1 c_s T \frac{\partial T}{\partial t} + \rho c_b c_s T \frac{\partial P}{\partial t} + \mathbf{n} \rho c_b \frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{n} K_f (1-n) K_r \mathbf{I} \nabla T) \\
- \rho c_s T \beta_0 \frac{\partial P}{\partial t} + (1-n) \rho c_s \frac{\partial T}{\partial t} = \nabla \cdot (\mathbf{n} K_f (1-n) K_r \mathbf{I} \nabla T) \\
\mathbf{n} \cdot \nabla \mathbf{V} \mathbf{T} - \mathbf{n} \rho c_s \nabla T \\
\mathbf{P}(x, y, z, t)\big|_{\partial \Omega} = \phi_0 (x, y, z) \\
\mathbf{T}(x, y, z, t)\big|_{\partial \Omega} = \omega_0 (x, y, z) \\
\mathbf{P}(x, y, z, t)\big|_{\Gamma_1} = \phi (x, y, z) \\
\mathbf{T}(x, y, z, t)\big|_{\Gamma_1} = \omega (x, y, z)
\end{align*}
\]

where: \(n\) - effective porosity; \(\rho\) - groundwater density (Kg/m\(^3\)); \(K_p\) - tensor of seepage (m\(^2\)); \(\mu\) - viscosity (Pa\cdot\text{s}); \(\rho_s\) density of porous medium (Kg/m\(^3\)); \(K_f\) - heat conductivity of water (W/m\cdot\text{°C}); \(K_s\) heat conductivity of medium (W/m\cdot\text{°C}); \(C_f\) specific heat capacity of water(J/kg\cdot\text{°C}); \(C_s\) specific heat capacity of medium (J/m\(^3\)\cdot\text{°C}); \(\beta_p\) compression coefficient (1/Pa); \(\beta_f\) - heat expansion coefficient (1/°C); \(\alpha_p\) compression coefficient of medium (1/Pa); \(I\) is three-order identity matrix; \(\mathbf{D}\) is tensor of mechanical heat dispersion (W/m\cdot\text{°C}); \(\mathbf{v}\) is porous flow velocity (m/s); \(P\) is groundwater pressure (Pa); \(T\) is temperature of water and porous medium (°C).

An analytical solution is very difficult to obtain since the partial differential equation is highly nonlinear, numerical finite difference method can be used to solve the equation. Partial differential equations, as well as mathematical models from their definite conditions, are preliminarily necessary for numerical solution. Numerical method is to decouple partial differential equation incorporating initial and
boundary conditions and form a large set of equations which are solved to get hydraulic pressure and temperature of each ay any moment node in the modeled domain.

To get numerical solutions, the discretization of research domain is required to be made in three dimensions. The elements are smaller near the pumping well and increase far away. And a uniform temporal discretization step, 5 days, is used in the model. Generally heating period is 1 month longer than cooling one; long-term operation will consume some shallow geothermal energy which in turn will result in a decrease in temperature. A suitable solution can be obtained by adjusting borehole space in the model till temperature constraints are satisfied (see Table 1).

The span of groundwater flow field and thermal field can be obtained according to the hydraulic pressure and temperature in each node. Of which the former is bounded to lifting amplitude, 5cm, outside the field and the latter is limited to 14.99°C. Table 1 summarizes the calculated results, one can see that influence radius of thermal field is the half of that of flow field.

Now it comes to the question that the load capacity is calculated with span of hydrodynamic or thermal field? To answer this question, it requires carrying out interference analysis of thermal field in adjacent pumps. Figure 2 represents the field configuration with influence radius R and borehole space d. The thermal field of two heat pumps does not show any interference and a certain space exists while R is used as influence radius of hydrodynamic field. And mutual interference of two thermal fields is negligible when R is taken as influence radius of thermal field. Which are illustrated clearly in Figure 3 and 4. Therefore, the load capacity is lower estimated while using hydrodynamic span and more reasonable with thermal influence factor.

The transformed energy can be calculated from thermodynamic equation, 

\[ P_i = C_w \rho_w V_w \Delta T \times 2.778 \times 10^{-7} / 24.0 \]

Where \( P_i \) is the capacity value of the aquifer in the i-th subdomain (KW), \( C_w \) is the specific heat capacity (4182.5J/Kg•C), \( \rho_w \) is the water density, \( V_w \) is groundwater discharge (m3/d), \( \Delta T \) is temperature difference of energy extract (°C); \( 2.778 \times 10^{-7} \) is the coefficient of thermal transformation. The calculated \( P_i \) at 7°C are listed in Table 1, the area of thermal field, \( A_i \), can be obtained from influence radius. The ratio of \( P_i \) to \( A_i \), is defined as the capacity of a unit area of aquifer, which is listed in Table 1.

![Figure 3](image1.png) **Figure 3.** Temperature distribution of neighboring pumps in 19th subdomain with R as hydrodynamic influence radius at the end of heating period of the 15th year.

![Figure 4](image2.png) **Figure 4.** Temperature distribution of neighboring pumps in 19th subdomain with R as thermal influence radius at the end of heating period of the 15th year.

### 3.2 Energy balance method and thermal storage method

Energy equilibrium and thermal storage methods are static ones with unit area of aquifer as study objective, groundwater pumping/rejection process is not taken into account in the estimation process.

Based on interannual change of temperature at the moment of annual heat unbalance, energy
equilibrium method assesses load capacity with temperature as constraints. With 120 days of heating period and 95 days of cooling period in Beijing city, heat loss is inevitable in the field, thus ground temperature decrease is resulting. With the supposed conditions, a 15-year performance period, 15°C as initial temperature. Under the condition of $7^\circ C$ temperature difference, the temperature of rejection water not less than 5°C can be ensured when the average annual temperature is not less than 12°C, correspondingly a long-term performance of heat pump system can be surely guaranteed. Thus annual temperature decrease, $\Delta T$, should not be smaller than 0.2°C. Thermal loss induced by temperature decrease can be calculated according to $\Delta E = C_v \times V \times 0.2$, $C_v$, effective specific heat capacity, is defined as $C_v = n \rho_f C_f + (1 - n) \rho_s C_s = nC_vf + (1 - n)C_v$, where all the parameters have the same physical meaning mentioned before. Based on the theory of energy equilibrium, $\Delta E$ is the difference between heat energy demanded in winter and cold energy in summer. So it comes out $C_v \times V \times 0.2 = P \times (120 - 95) \times 24 \times 3.6 \times 10^6$, it follows $P = 9.26 \times 10^{-11} C_v V$, finally the load capacity of per unit aquifer area, $P_A$, written in terms of $C_v$ and $M$, $P_A = 9.26 \times 10^{-11} C_v M$. Table 1 summarizes the calculated $P_A$ results.

The annual heat imbalance is not taken into account in thermal storage method. The average of heating or cooling period is 107.5 days in Beijing city. It is supposed that heat injected to the ground in summer can balance the amount extracted in winter, and temperature difference, $\Delta T$, is $7^\circ C$. The total heat in an aquifer is defined as $E_r = E_s + E_w$, where $E_s$ is the heat stored in the grains (J), which takes form $E_s = (1 - n) \rho_s C_s M A \Delta T$, $E_w$ is the heat in the void (J), and is given by $E_w = n \rho_f C_f M A \Delta T$. After a substitution, we get $E_r = C_v M A \Delta T$, so load capacity of per unit aquifer area is obtained through $P_A = E_r / (At) = C_v M A \Delta T / t = 2.778 \times 10^{-7} C_v M A \Delta T / (107.5 \times 24) = 7.54 \times 10^{-10} C_v M$, the calculated results are listed in Table 1.

### 3.3 Classes of loading capacity

It is can be seen from Table 1 that some notable differences exist in the three methods. The value calculated from thermal storage method is distinctly larger than those of balance method and numerical method. The estimated $P_A$ values with energy equilibrium method is close to that of numerical method, 0.9~2.7 times, while the estimated values from thermal storage method is 7~19 times of those values from numerical method. Consequently the estimated value with thermal storage is 8.1 times of those with energy equilibrium method according to the calculation equation.

The differences among the three methods have been demonstrated. In numerical method, it is supposed that the site is an open system, where exists energy transfer. As a dynamic method, it represents the behavior of groundwater pumping/rejection based on the high efficiency of heat pumps. However energy equilibrium method and heat storage method are statics, which suppose that the site is a closed system without energy exchange, and assure temperature in any point increases/decreases in the same amplitude, which is not a reality. The only difference is that energy balance method applies temperature constraint while thermal storage method does not. In view of above analysis, one can conclude that the estimated results with numerical method are more reliable.

The calculated $P_A$ value is not related to the permeability coefficient, but linearly and positively related to the aquifer thickness, which is consistent with the fact that $P_A$ and $C_v M$ derived from equilibrium method and thermal storage method, are proportional. Due to little difference between specific heat capacity of each aquifer but large difference in the thickness $M$, correlation between $P_A$ and $M$ is remarkable. Figure 5 illustrates the relationship between $P_A$ obtained with three methods and $M$. 

### Table 1. Load capacity of groundwater heat pumps in unit aquifer area of each sub-domain

<table>
<thead>
<tr>
<th>No. of Subdomain</th>
<th>Water yield capacity (m$^3$/d)</th>
<th>Borehole space (m)</th>
<th>Effective radius of hydrodynamic field (m)</th>
<th>Effective radius of thermal field (m)</th>
<th>Load capacity (KW)</th>
<th>span of thermal field (km$^2$)</th>
<th>Load capacity of unit area (KW/km$^2$)</th>
<th>Numerical method</th>
<th>Balance method</th>
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</table>

Six levels are classified according to PA values, namely $1000 \sim 1600 \sim 1600 \sim 2200 \sim 2200 \sim 2800 \sim 3400 \sim 3400 \sim 4000 \sim 4000 \sim 4600$, after regroups of hydrogeological subdomains (see right of Fig. 5).

It is founded that from Table 1 and the Fig.6, the load capacity is significantly larger in south-east plain and alluvial-pluvial fan due to a larger thickness compared with the piedmont in the west. There is great concern for administrative sectors about the groundwater rejection rate during the operation of groundwater heat pumps, the higher rejection rate, the higher efficiency of water resources utilization, the smaller impact on water resource. The piedmont aquifer is mainly consists of coarse sand gravels and easy to be rejected, on the contrary south-east plain mainly contains fine sand, which makes groundwater difficult to reject into the aquifer. Therefore, the load capacity contradicts the difficulty of groundwater rejection, that is to say, the area with larger load capacity is difficult to be rejected, and vice versa. Based on this discovery, GWHP should be applied with small areal density in piedmont, in contrast, it can be utilized with large areal density in south-east plain but some special attention should be paid to take some measure in order to assure the high efficiency of groundwater rejection.
4. Conclusions

Ground thermal transfer, equilibrium method and thermal storage method are applied to evaluate load capacity of per unit area of aquifer on GWHP. The later two methods are static ones which suppose heat pump site is a closed system where does not consider exchange and process of groundwater pumping/rejection, so the estimated results are slightly larger. On the contrary, numerical method takes the heat pump site as an open system and heat exchange and groundwater pumping/rejection are taken into account in the model, one the other hand, with temperature as constraints, which ensures the long-term performance efficiency, the estimated results obtained in numerical method are better than those from other two methods.

The load capacity is divided into six classes according to the results obtained from numerical method, which is positively related to the aquifer thickness and contradicts the difficulty of groundwater rejection. A large load capacity exists in south-east plain but difficult for groundwater rejection, in contrast, it is easy for groundwater rejection in alluvial and pluvial fan of big river, but with a smaller load capacity.

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References