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Estimating Thermal Impact on Groundwater Systems from Heat Pump Technologies: A Simplified Method for High Flow Rates

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Abstract: This research delves into the potential thermal effects on underground water systems caused by the use of thermal technologies involving extraction and injection wells. We developed a unique approach that combines straightforward calculations with computer-based modeling to evaluate thermal impacts when water flow rates exceed 2 L/s. Our model, based on a system with two wells and a steady water flow, was used to pinpoint the area around the thermal technology where the temperature varied by more than 1 °C. Our findings suggest that the data-based relationships we derived from our model calculations provide a cautious estimate of the size of the affected area, or 'thermal cloud'. However, it is important to note that our model's assumptions might not fully account for the complex variables present in real-world underground water systems. This highlights a need for more research and testing. A key contribution of our study is the development of a new method to assess the thermal impact of operations involving heat pumps. In conclusion, while our proposed method needs more fine-tuning, it shows promise in estimating temperature changes within water-bearing rock layers, or aquifers. This is crucial in the effective use of thermal technologies while also ensuring the protection and sustainable management of our underground water resources.

Keywords: groundwater; heat pump; thermal feedback; well doublet; analytical solutions

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1. Introduction

Groundwater heat pump (GWHP) systems have emerged as a sustainable solution for heating and cooling in various settings, based on the thermal stability of the subsurface environment [1,2]. However, these systems are not without complexity. The design and operation of GWHP systems require a thorough understanding of the thermal and hydraulic dynamics of the subsurface, which can be complex and very specific to the site [3,4].

Historically, researchers have attempted to address these complexities through a variety of analytical and numerical methods [5–7]. However, these methods often depend on simplifying assumptions, such as steady-state conditions and advection-dominated transport, which may not accurately represent the dynamic nature of real-world GWHP systems [8,9].

The development of advanced computational capabilities and modeling techniques has launched a new era of possibilities for more accurate and detailed assessments of GWHP systems [10,11]. For instance, numerical models can now account for the transient nature of thermal loads and the spatial variability in subsurface properties, providing a more realistic representation of system dynamics [12–14].

One of the critical areas of research in this field is the estimation of the thermal impact on groundwater systems from GWHPs [5,15,16]. A comprehensive understanding of the thermal effects on groundwater systems is crucial for the design, implementation, and management of these technologies. Pioneering works in this area, such as [15], have developed mathematical models to investigate the transient temperature behavior of production wells during the reinjection of heat-depleted water into aquifers with a uniform regional flow.

However, a significant challenge identified in the literature is to estimate the thermal impact on groundwater systems at high flow (pumping) rates, particularly those exceeding 2 L/s [5,17]. This article seeks to address these challenges and knowledge gaps. Our goal is to develop a novel method based on analytical calculations that accelerates the process of assessing thermal impacts on groundwater systems for flow rates higher than those currently estimated. This paper, based on [5,17,18], exhaustively examines these theoretical proposals and, through rigorous testing and experimentation, aims to extend the scope of these models and propose a more reliable, comprehensive approach.

By utilizing simplified methods with improved accuracy, the adoption and application of environmentally friendly heating and cooling technologies are applicable while ensuring that their operation has minimal adverse impacts on our crucial groundwater resources.

2. Materials and Methods

2.1. Hydraulics of a Two-Well Heat Pump System

In order to utilize analytical formulas, specific conditions and limitations were considered. A two-well system (pumped and injected) was used in the direction of groundwater flow. The water-bearing layer was an infinite plane of constant thickness with a stressed surface and a uniform water flow. The schematic situation is depicted in Figure 1.

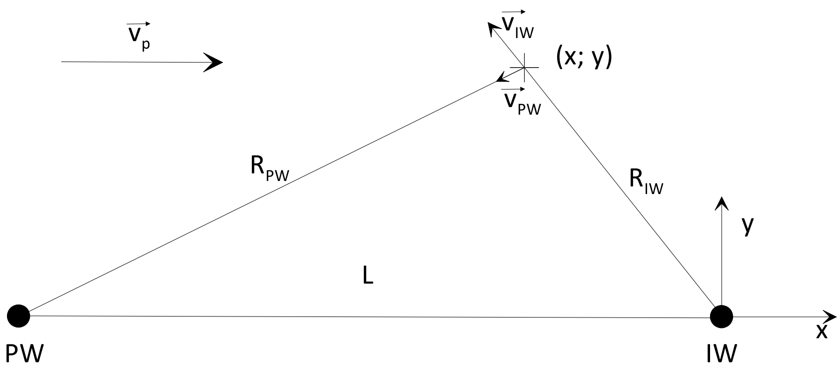

Figure 1. Schematic diagram of the situation of the heat pump well.

The coordinate system was positioned in place of the injected well, with the orientation of the *x*-axis in the direction of an undisturbed medium flow. In this case, the well coordinates were $(0;\ 0)$ for the pumped well and $(-L;\ 0)$ for the injected well, and the vector of the natural fluid flow had the form $\vec{v_p} = (v_x; 0)$.

First, the hydraulic aspect of the problem was addressed. From the principle of superposition, it follows that the velocity at any point is determined as the vector sum of the natural velocities resulting from the pumping and injecting wells in the following form:

$$\vec{v_c} = \vec{v_p} + \vec{v_{PW}} + \vec{v_{IW}} \tag{1}$$

In the case of a confined head, it is possible to express the steady velocity field in the vicinity of a well in an infinite water layer with thickness b from the continuity equation. The velocity field was determined based on the position and amount of water being pumped Q:

$$\vec{v_c}(x, y, Q) = k\,\vec{\imath} + \frac{-Q}{2\pi R_{PW} b}\,\vec{J}_{cs} + \frac{Q}{2\pi R_{IW} b}\,\vec{J}_{IW} \tag{2}$$

where

$\vec{J}_{PW}$ is the unit vector in the direction of $\vec{v}_{PW}$;
$\vec{J}_{IW}$ is the unit vector in the direction of $\vec{v}_{IW}$;
$R(x; y)$ are the distances to the relevant well, as shown in Figure 1;
$\vec{v}_C$ expresses the Darcy velocity of the steady fluid flow at each point in space;
b is the thickness of the water layer;

k is the hydraulic conductivity;
x *and* y are the spatial coordinates;
Q is the quantity of pumped water;
$\vec{i}$ is the slope vector of the groundwater level with amplitude i.

For the purposes of the task, it was essential to distinguish between two situations. In the first case, some of the water from the injection well returned to the pump well (the wells mutually influenced each other hydraulically). In the second case, the water from the injected well did not flow back into the pump well (the wells were hydraulically separated). Hydraulic separation of the wells therefore indicates that the water in the pumped well will not be affected by the injection of thermally influenced water into the injected well. Hydraulically separated wells ensure temperature stability and thus the functionality of the technology. However, in practice, most technologies are not actually hydraulically separated. Even lower amounts of pumped and injected water are usually associated with the flow of some of the injected water back into the pumped well in natural groundwater flows. Despite this situation, technology can still be functional during the utilized seasons. Hydraulic separation of wells occurs exactly when the component of the total velocity in the x direction on the line is greater than 0.

$$\left[\vec{v_c}\left(-\frac{L}{2};0;Q\right)\right]_X > 0 \tag{3}$$

This condition is met exactly when [19]

$$L > \frac{2Q}{T\pi i} \tag{4}$$

where $T = kb$ is the transmissivity coefficient of the medium, L is the distance between the wells, and Q is the quantity of pumped water. Absolute non-influence of the wells occurs only in the case of a very large distance between the wells or when the pumped amounts are small.

The same conditions for the hydraulic separation of wells in the heat pump system are also stated in [5,18].

With the existence of backward flow between wells, it was necessary to quantify its magnitude. For this purpose, the speed of groundwater flow was expressed on the axis between the wells (a line in our chosen coordinate system). From symmetry $\vec{v_c}$, it follows that the velocity component in the direction of the "y" axis on this axis is always zero. It represents $\left[\vec{v_c}\left(\frac{L}{2};y\right)\right]_x = \left|\vec{v_c}\left(\frac{L}{2};y\right)\right|$. This speed on the axis was expressed as follows:

$$\left|\vec{v_c}\left(\frac{L}{2};y\right)\right| = ki - \frac{QL}{2\pi b}\frac{1}{y^2 + \left(\frac{L}{2}\right)^2} \tag{5}$$

For the backward flow of water into the pumped well, there is an area for the values of the parameter y in the interval $(-Y;\ Y)$ where the speed $[v_c]_x < 0$. The entire backward flow to the well will pass through this area on the well axis (Figure 2). The magnitude of the backward flow from the injection well to the pumping well was expressed as follows:

$$\begin{aligned} Q_{back} &= \int_{-Y}^{Y} -\left|v_c\left(\tfrac{L}{2};y\right)\right| b\, dy \\ Q_{back} &= -2kibY + \tfrac{2Q}{\pi}\arctan\tfrac{2Y}{L} \end{aligned} \tag{6}$$

Y is the distance on the x axis at $L/2$ where $|vc| = 0$ (Figure 2). After substitution into Equation (5), the following equation was obtained for the distance Y:

$$Y = \sqrt{\frac{QL}{2\pi bki} - \left(\frac{L}{2}\right)^2} \tag{7}$$

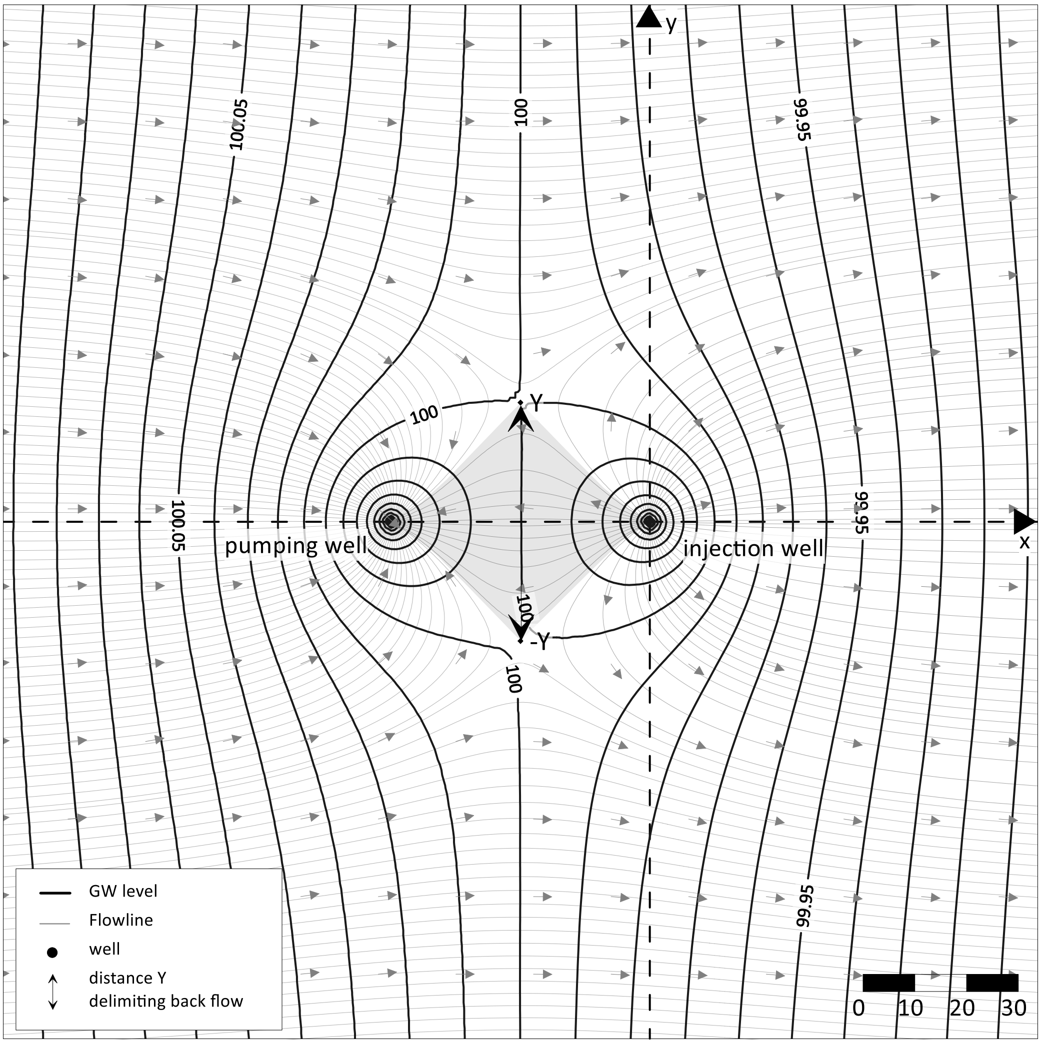

Figure 2. Context of groundwater level and flow lines around the heat pump with backward water flow between wells.

Similar analytical equations evaluating these parameters can be found in [20].

2.1.1. Characteristics of the Heat Pump System

In open-loop water-to-water heat pump systems, the degree of influence of the temperature of the pumped water on the temperature of the water flowing back from the injected well to the pumped one is significant. This effect of backflow reduces the system's efficiency, or leads to the same cooling output, leading to increased water extraction (which worsens the back influence). If there is a natural water flow, part of the heat-affected water exits the area of use, even when the same amount is pumped and infiltrated. Hence, water-to-water heat pump systems thermally impact the groundwater in their surroundings, following the flow of groundwater. During the technology approval process, it is necessary to limit this thermal influence on the geological environment due to possible negative impacts on the quality of groundwater. It is also crucial to evaluate whether the technology explored does not hinder the functionality of existing water-to-water systems nearby.

2.1.2. Determining the Backflow to the Pumping Well

The ideal case for a heat pump occurs when no heated water returns to the pumping well in a natural flow. In the preceding chapter, the condition of no backwater flow between wells was introduced by Equation (4). The same condition is also stated in [5,18]. If this condition is met, the wells will not thermally influence each other. However, if a portion of the water from the injected well flows back to the pumped well, the water in the pumped well will be thermally affected. This thermal effect will change over time and will depend on the hydraulic and transport characteristics of the groundwater flow. Even in a fairly simple natural flow system with a pumped well and an injection well, there is no straightforward analytical solution. However, it is possible to determine the water arrival time from the injection well to the pump well and use this interval to conservatively restrict the possible use of heat pumps during the cooling or heating season. If, however, this determined time indicates the non-functionality of the technology, the calculations will need to be refined via numerical modeling, which is more accurate.

Even when complete hydrodynamic separation of the pumped and injected wells is not detected, it is possible to use heat pumps. As mentioned, the arrival time of the heat to the injected well is an essential factor. For the heat flow, one must know the time of arrival of the water time between the two wells and the retardation factor R.

Based on Equation (4), we chose the parameter β in the following form:

$$\beta = \frac{2Q}{kb\ \pi i L} \tag{8}$$

Well interference occurs when $\beta > 1$. The published relationship for the groundwater flow time t_{hyd} between the wells [5] in the following form was used:

$$t_{hyd} = \frac{Ln}{Ki}\left[\frac{\beta}{\sqrt{\beta - 1}}\arctan\left(\frac{1}{\sqrt{\beta - 1}}\right) - 1\right] \tag{9}$$

where n is the porosity of the rock environment.

For the calculation, a quantity called the retardation coefficient R was needed, which expresses the deceleration of heat propagation due to heat exchange between water and the rock environment. The retardation coefficient is determined by the following equation [21]:

$$\frac{1}{R} = \frac{v_{the}}{v_{hyd}} = \frac{nC_W}{C_{aq}} = \frac{nc_w\rho_w}{nc_w\rho_w + (1-n)c_s\rho_s} \tag{10}$$

v_{hyd} is the water flow speed in a porous environment;
v_{the} is the heat propagation speed in a porous environment;
c_w is the heat capacity of the water;
c_s is the heat capacity of the rock;
ρ_w is the water density;
ρ_s is the rock density;
C_w is the volume heat capacity of the water;
C_{aq} is the volume heat capacity of the water environment;
t_{the} is the time of the heat change transport which, because of the heat capacity of the environment, is greater than the groundwater flow time. From Equation (10), it follows that the ratio between t_{hyd} and t_{the} is

$$t_{the} = R\ t_{hyd} \tag{11}$$

From Equations (8) and (10) together, the formula for the heat input into the pumping well follows.

$$t_{the} = \frac{C_{aq}L}{C_W ki}\left[\frac{\beta}{\sqrt{\beta - 1}}\arctan\left(\frac{1}{\sqrt{\beta - 1}}\right) - 1\right] \tag{12}$$

The calculation for time does not include diffusion and dispersion effects, so the temperature in the pumping well will gradually increase. The time t_{the} represents a boundary at which the thermal influence disrupts the usability of the heat pump.

2.2. Thermal Impact on Surroundings

To estimate the extent of thermal impact, the procedure published in [17] was first verified. This article describes the following three analytical solutions for heat transport in an environment:

- The radial transport model;
- The linear advective model of heat transport;
- The planar advective model of heat transport.

Taking into account the thermal influence on the surroundings of a two-well system under natural groundwater flow, the planar advective model was selected as the most suitable approximation for the heat transport of the problem because it considers the impact of the local hydraulic gradient on the heat distribution around the well. In the following text, the equations according to which the method determines the thermal influence on the surroundings and the variables that appear in them are described.

Table 1 presents a list of physical quantities with the labels used in the calculations.

Table 1. Variables included in the analytical calculation.

Variable	Symb	Unit
Temperature gradient of poured water	ΔT_{inj}	K
Temperature gradient in the source term	ΔT_0	K
Width of the source term	Y	m
Poured amount of water	Q	m^3/s
Seepage velocity	v_a	m/s
Specific heat capacity of substance x (w—water; s—solid)	c_x	J/(kg·K)
Volumetric heat capacity of substance x (w—water; s—solid)	C_x	J/(m^3·K)
Density of substance x (w—water; s—solid substance)	ρ_x	kg/m^3
Thermal conductivity of substance x (w—water; s—solid)	λ_x	W/(m·K)
Dispersion (transverse longitudinal)	$\alpha_{T,L}$	m
Retardation coefficient	R	---

The source term was an area perpendicular to the direction of groundwater flow in the environment. The area had a height equal to the depth of the aquifer. In [17], the authors introduced two models for the width of the source area:

$$Y_0 = \frac{Q}{2bki} \tag{13}$$

$$Y_{max} = \frac{Q}{bki} \tag{14}$$

The thermal power supplied to the environment was determined based on the volumetric heat capacity of water C_w, the amount of poured water Q, and the temperature gradient between the poured and pumped water ΔT_{inj} according to the following relationship:

$$q_h = \Delta T_{inj} C_w Q \tag{15}$$

From the thermal power, it was possible to determine the thermal gradient on the surface according to the following equation:

$$\Delta T_0 = \frac{q_h}{b v_a n C_w Y} \tag{16}$$

The properties of the environment related to the thermal flow were characterized for further needs by the quantity $D_{x,y}$, which includes heat diffusion via thermal conductivity and the expansion of the thermal cloud based on dispersion (transverse and longitudinal), according to the following relationship:

$$D_{x,\,y} = \frac{\lambda_m}{n C_w} + \alpha_{L,T} v_a \tag{17}$$

The equation of temperature change propagation in the environment using a natural flow with diffusion and dispersion was analytically expressed under the given conditions as follows:

$$\Delta T(x,\ y,\ t) = \left(\frac{\Delta T_0}{4}\right) erfc\left(\frac{Rx - v_a t}{2\sqrt{D_x R t}}\right)\left\{ \text{erf}\left[\frac{y + \frac{Y}{2}}{2\sqrt{\frac{D_y x}{v_a}}}\right] - \text{erf}\left[\frac{y - \frac{Y}{2}}{2\sqrt{\frac{D_y x}{v_a}}}\right]\right\} \quad (18)$$

The equation describes the spread of the temperature gradient and does not depend on the background temperature of the environment.

In Equation (18), there is also a unit of time. Heat pumps can be used for both cooling and heating. In the calculations, a period of one heating or cooling season of 6 months was assumed.

The method provides a sufficiently accurate solution only for small amounts pumped at up to 2 L/s and with the conditions described in the given article [17]. In attempts to expand this method to larger amounts of pumped water, it was not possible to obtain sufficiently representative results. The main problem with this method lies in the assumption of an almost undisturbed fluid flow at a certain distance from the well. However, this condition is not met for pumping larger amounts. In the wider vicinity of the well, the natural flow in the environment is affected by pumping. The influence increases with the amount of pumped water and the reduction in the amount of the natural flow of groundwater.

3. Results

3.1. Empirical Methods

In the next part of this work, an approximate conservative dependency was determined for larger amounts of pumped water, estimating the size of the cloud from the pumping parameters and the hydraulic and transport parameters of the environment. A conservative dependency, means a safe (overestimated) estimate to determine the range of temperature changes. A numerical model of heat propagation was compiled in a water-saturated environment under simplified conditions, namely neglecting heat loss to the surrounding environment. This is a conservative limitation since heat exchange with the surface and substrate reduces the reach of the thermal impact on the surroundings. MODFLOW [22] and MT3D [23,24] software were used to create the model.

The numerical model was developed based on the assumptions described in the analytical solution mentioned earlier for a homogeneous, isotropic, infinite aquifer with constant thickness, a hydrostatic pressure level, and a uniform flow of groundwater. The boundary conditions of a constant level were chosen in the model far enough so that they had no impact on the actual flow around the wells. The computational grid had the densest area around the infiltration well of a size of 150 × 150 m, with a cell size of 2 × 2 m. Toward the edges of the model, the cell size gradually increased.

For a conservative possibility of verifying the impact of thermal technology on surrounding groundwater, typical curves of temperature change propagation in groundwater were empirically determined by analyzing the modeling results with a larger pumped amount.

Model solutions were sought for the case of the typical hydraulic and thermal properties of gravel–sand aquifers (Table 2). The selected parameters of the system and groundwater flow were changed (Table 3). The values in Tables 2 and 3 are typical values for alluvial sediments in Slovakia. The environmental parameters related to heat capacity and conductivity remained unchanged since they do not change much for aquifers usable with the technology of water–water heat pump systems.

Table 2. Used parameters of the gravel–sand aquifer.

Parameter	Unit	Value
Water density	kg/m^3	1000
Specific heat capacity of water	J/(kg·K)	4180
Rock density—quartz	kg/m^3	2600
Specific heat capacity—quartz	J/(kg·K)	820
Thermal conductivity of porous environment	W/(m·K)	2.5
Longitudinal dispersion	m	1.8
Transverse dispersion	m	0.18

Table 3. Range of varying system parameters for individual series of calculations.

Parameter	Unit	Value Range
Thickness of aquifer	m	4–20
Pumped amount of water	L/s	0–10
Distance of wells	m	30–100
Groundwater gradient	m/m	0.0005–0.002
Hydraulic conductivity	m/s	1×10^{-3}–5×10^{-3}

A series of calculations with varying parameters was performed in which the maximum width (Y_{cloud}) and length (X_{cloud}) of the thermal cloud were determined (Figure 3). For all cases, the heat transport was modeled for a period of 6 months, which represents an estimate of the period of using heat pump technology in cooling or heating mode during the year. The undisturbed temperature of the groundwater was 12 °C in the calculations, and the temperature of the heated water poured into the infiltration well was 24 °C. The usual temperature of groundwater is 12 °C, and a temperature of 24 °C is the highest permitted temperature of water infiltrating the rock environment in the Slovak legislation. With the model, the area around the thermal technology in which the temperature changed by more than 1 °C was determined. Temperature changes in space do not have a linear dependency. However, it can be stated that the determined typical curve will represent the place where the temperature change will be 1/12 of the difference between the temperatures of the poured water and the surrounding water (it is the ratio of the determined change in the groundwater temperature and the modeled maximum temperature change at the location of the infiltration well).

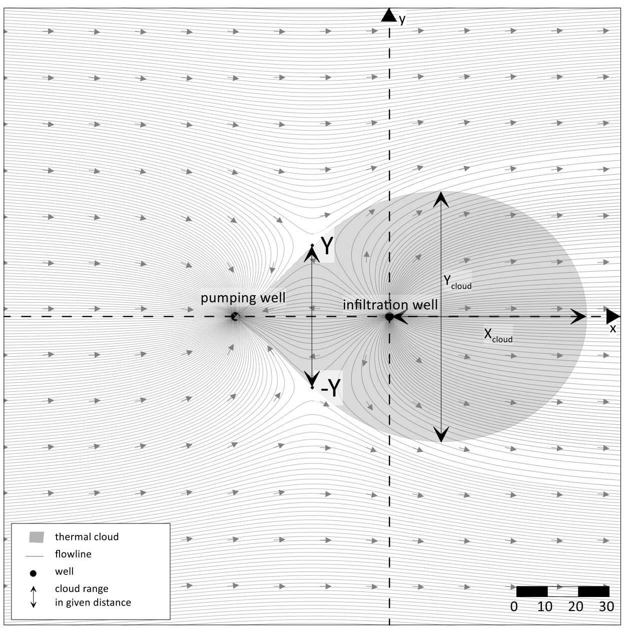

Figure 3. Range of the thermal cloud with marked width (Y_{cloud}) and length (X_{cloud}).

From the results of modeling individual cases of heat transport, curves were determined that safely delimit the calculated values of the extent of the thermal change area. The curves obtained represent a conservative estimate of the dimensions of the thermal cloud after half a year of using thermal technology.

From a time perspective, it is not possible to examine the results of the calculations for the entire range of input parameter values in Table 3 within this task. The series of calculations listed in Table 4 were performed. In each series, the pumped amount varied in the range of 0–30 L/s.

Table 4. Overview of the parameters of individual series of calculations.

Parameter	k	b	n	L	I
Unit	m/s	m		m	m/m
Series 1	0.00125	10	0.3	50	0.001
Series 2	0.00125	10	0.3	50	0.002
Series 3	0.00125	10	0.3	50	0.0005
Series 4	0.00125	2.5	0.3	50	0.001
Series 5	0.00125	10	0.22	50	0.001
Series 6	0.00125	10	0.3	20	0.001
Series 7	0.004	10	0.3	50	0.001
Series 8	0.001	4	0.3	50	0.001

3.1.1. Cloud Length

The length of the thermal cloud, starting from the infiltration well, was determined as the distance of heat transport in the natural flow and the additional distance of heat transport due to pumping and pouring into the wells. The radius of temperature change from the heat source in the natural flow of groundwater for t = 182 days is expressed as follows:

$$x_{natural} = \frac{ki}{Rn}\, t \tag{19}$$

R is the retardation factor, which expresses the ratio between the speed of propagation of water and the speed of propagation of temperature in a porous environment. It is caused by heat exchange between water and the rock environment. It depends on the thermal parameters of the water and the rock environment. A typical value of $R = 3$ was used for the calculation.

Based on the results of the modeling, a graph was compiled (Figure 4) of the dependence of the additional distance x' on the parameter p, expressed as

$$p = \frac{Q(1 - Q_{back})ki}{nb} \tag{20}$$

The graph shows the modeled distances from the change in groundwater temperature by 1 °C depending on the parameter p. A curve delimiting the calculated values was determined, assuming that pumped amounts larger than 10 L/s do not necessarily fall under this curve. However, the shape of the curve is also influenced by the results of the calculations, with yields greater than 10 L/s. The conservative delimiting curve obtained in this way is shown in Figure 4. The curve is described by the following function:

$$x' = 46944.56\, p^{0.33} + 9.71 \tag{21}$$

The final length of the cloud will be limited by the data from the delimiting curve:

$$X_{cloud} = \frac{ki}{Rn}\, t + 46944.56 \left(\frac{Q(1 - Q_{back})ki}{nb} \right)^{0.33} + 9.71 \tag{22}$$

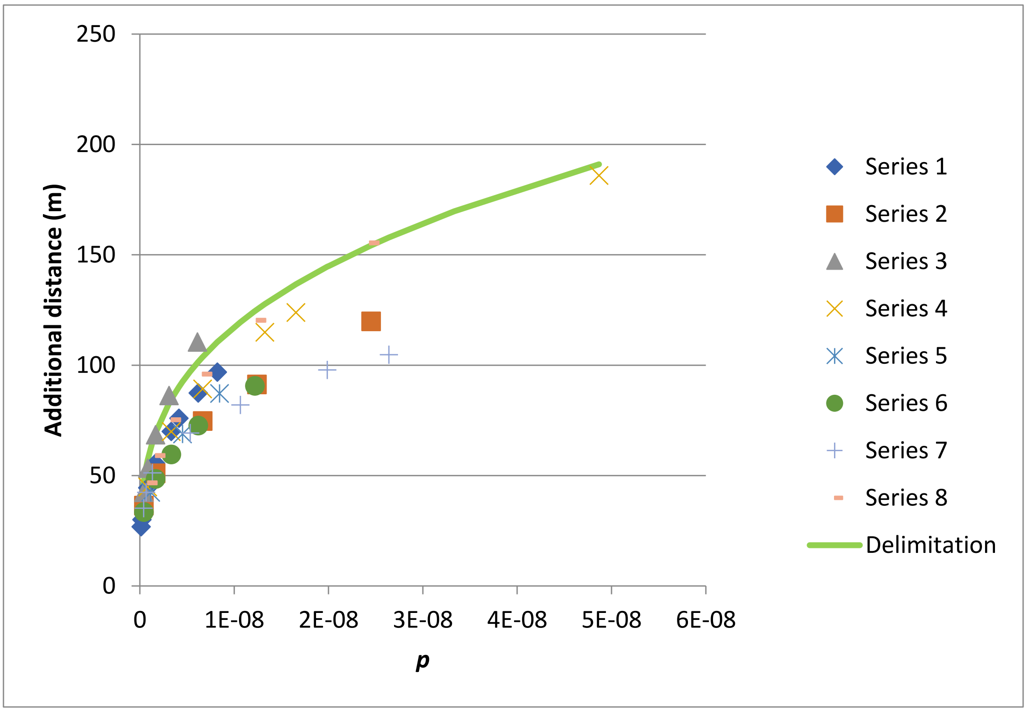

Figure 4. Graph of the dependence of the additional distance on environmental parameters.

3.1.2. Cloud Width

For the maximum width of the thermal cloud, its dependence on the width of the return flow between the wells was calculated. The width of the entire return flow is $2Y$ (Equation (7)). In the case of hydraulically isolated wells, the distance Y was replaced by zero. In the graph shown in Figure 5, the resulting values of the width of the area of the temperature change of the groundwater by 1 °C depending on the value of $2Y$ are displayed.

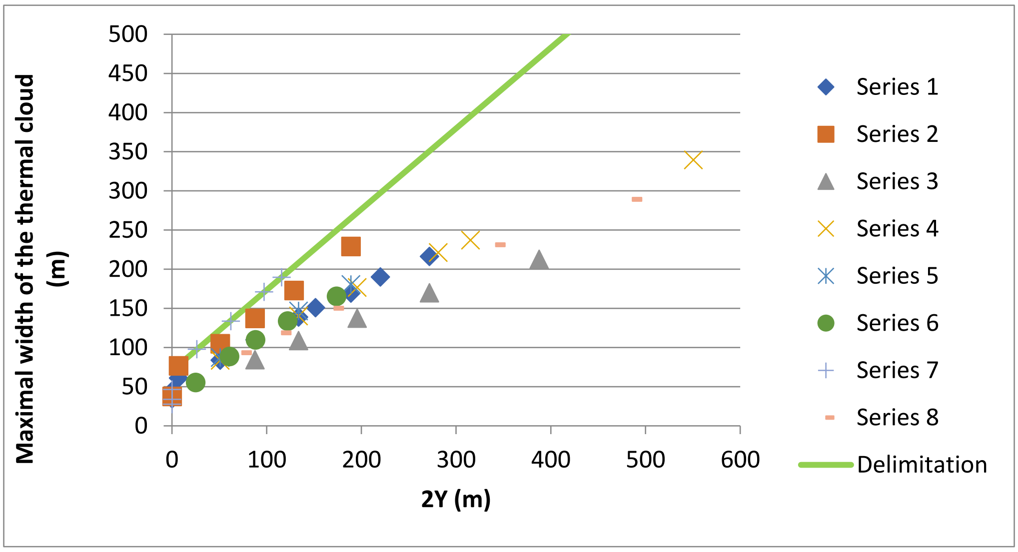

Figure 5. Graph of the dependence of the thermal cloud width on the return flow width between the wells.

This display represents a linear course of the observed dependence. Since the width of the return flow is zero for hydraulically separated wells, it is not possible to express the width of the thermal cloud for wells that do not influence each other. The determined delimitated half-line marked in Figure 5 is higher for all pumped amounts of hydraulically separated wells than the value of the intersecting curve at the zero point. From the evaluated data, it is possible to propose to set the boundary width of the cloud as data from the delimiting curve as follows:

$$Y_{cloud} = 1.031\ (2Y) + 70.35\ (23) \tag{23}$$

The delimiting curves (23) and (24) will need to be updated with further calculations.

3.1.3. Simplified Methodology for the Assessment of Heat Pump Technology

The assessment of heat pump technology comprises three stages:

1. The evaluation of the hydraulic separation of the wells. If the wells are hydraulically separated, there is no increase in temperature in the pumped well due to the inflow of already heated water. If the condition from Equation (4) is met, the wells are hydraulically separated, and one can advance to step 3. If not, progression to step 2 is required.
2. The determination of the time of temperature backflow. If the wells are not hydraulically separated, the resulting system can still be used until the thermally adjusted water flows back into the pumped well. From the Equation (9), the water flow duration (t_{hyd}) is calculated, and subsequently, the heat transport time (t_{the}) is derived from Equation (11). If the heat transport time is less than the number of days in the heating/cooling seasons, the wells thermally influence each other.
3. The estimation of the thermal cloud's extent. This involves determining the estimated dimensions of the thermal cloud that will spread into the surroundings according to Figure 3. The length of the cloud (X_{cloud}) is calculated from Equation (22), and the width of the cloud (Y_{cloud}) is calculated from Equation (23). It should be noted that the dimensions of the thermal cloud are ascertained based on the numerical modeling of an idealized scenario. These should be overestimated values, determined at a thermal gradient of 12 °C. The boundaries are selected lines at which the thermal change compared to the original state is 1 °C. If the gradient of the poured water is smaller, we cannot predict how the boundaries will diminish or expand, only that the temperature change on the given line will be directly proportionally smaller. Such calculated values are never superior to more precise calculations as this is a very rough approximation.

An Excel sheet, prepared for these calculations, is included in the Supplementary Material.

4. Discussion and Conclusions

In this study, a comprehensive series of calculations and modeling efforts were conducted to estimate the thermal impact on groundwater systems resulting from the implementation of heat pump technologies, with a specific focus on high flow rates in gravel–sand aquifers. The primary objective was to determine the maximum width and length of the thermal cloud, which represents the extent of temperature changes within the aquifer. The calculations were performed over a period of 6 months, corresponding to the typical duration of heat pump usage for cooling or heating purposes throughout the year. The undisturbed groundwater temperature was assumed to be 12 °C, while the temperature of the heated water introduced into the infiltration well was set at 24 °C, adhering to the highest permitted temperature according to Slovak legislation.

The modeling results provided valuable insights into the spatial distribution of temperature changes within the aquifer. By identifying the area where the temperature changed by more than 1 °C, the study established a reference point for assessing the thermal impact of heat pump technologies. Although temperature changes in space do not exhibit a linear dependency, a typical curve was identified to approximate the location where the temperature change is approximately 1/12 of the difference between the temperatures of the injected water and the surrounding groundwater. This ratio serves as an estimate of the change in groundwater temperature based on the modeled maximum temperature change at the infiltration well location.

Similar studies in the literature have also addressed the estimation of thermal impacts on groundwater systems resulting from heat pump technologies. Notably, [5,17] explored theoretical proposals that align with the objectives of this study. Ref. [5] emphasized the significance of the accurate estimation of thermal impacts, while the authors of [17] specifically focused on high flow rates. These studies, along with our research, contribute to the broader understanding of thermal impacts and provide valuable insights into the design and operation of heat pump systems.

Equations (22) and (23) safely estimate the extent of temperature changes but cannot assess the efficiency of the technology or the possibilities of its implementation in terms of functionality. In this study, a condition was defined in which part of the water from the injection well would flow back to the extraction well, i.e., the wells would affect each other hydraulically and thus thermally. The return flow to the extraction well reduces the efficiency of the technology because after the time needed for the flow from the injection to the extraction well, the temperature in the extraction well will change. This time is determined in Equation (12). If the technology is not used for longer than this time during the season, its efficiency will not be reduced. Otherwise, to determine the realistically usable amount of heat from the aquifer, more detailed solutions of numerical modeling will be needed under the conditions of the given technology.

Despite the advancements made in this study, it is important to acknowledge certain limitations. The proposed method relies on simplified analytical calculations and numerical modeling which may not fully capture the complexities inherent in real-world groundwater systems. Assumptions made in the model, such as steady-state conditions and advection-dominated transport, may not entirely represent the dynamic nature of heat pump systems. Additionally, the model assumes a two-well system and a uniform water flow which may not be universally applicable to all scenarios. Further research and testing are necessary to refine and validate the proposed method, considering a wider range of system configurations and aquifer characteristics.

In conclusion, this study successfully proposed and verified a method for estimating the extent of temperature changes within aquifers resulting from the implementation of thermal technologies utilizing extraction and injection wells. The empirical dependencies derived from the model calculations provide a conservative estimate of the dimensions of the thermal cloud. For flow rates up to 10 L/s in gravel–sand aquifers, these dependencies are deemed safe and reliable for determining the dimensions of thermal clouds. However, if the calculated influence in a given area raises concerns, more sophisticated numerical modeling techniques are required to accurately determine the actual extent of temperature changes within an aquifer. By addressing these limitations and conducting further research, the accuracy and applicability of the proposed method can be enhanced, facilitating the implementation of thermal technologies while ensuring the protection and sustainable management of groundwater resources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrology10120225/s1.

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