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Environmental Compliant Planning of Shallow Geothermal District Heating Using Numerical Groundwater Models

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ABSTRACT

The direct usage of shallow groundwater resources in open loop systems for district heating is attractive due to the higher coefficients of performance of the heat pump which can be achieved compared to closed loop systems. Groundwater coupled heat pumps are well established on the growing market for renewable energy but they require more detailed planning due to the environmental impact of the pumping and injection process. Typically, the systems are popular on household scale, but recently pilot concepts for district heating have been started in Germany. Advantages are low construction and operating costs and absence of circulating potentially harmful fluids. However, abstraction and injection rates may reach more than 1000 m³/day, thus requiring environmental impact assessment in the planning process. The paper explores the use of numerical groundwater models for optimizing the well positions as well as for avoiding potential conflicts of interest with other groundwater users. Based on three pilot studies, it is demonstrated how shallow groundwater sources can be utilized for district heating. Existing analytical solutions for the spreading of cold water plumes in aquifers are compared to numerical solution using finite elements. The numerical models can also serve to study seasonally changing directions of the open loop systems, thus actively using the aquifer as heat storage during summer time operation.

1. INTRODUCTION

Geothermal energy may be extracted either from shallow or deep drillings and used either for electricity production or for heating purposes. The vast majority of economical successful uses of geothermal energy have been for heating rather than for electricity production. Especially ground source heat pumps are well established on the market. However, the direct use of groundwater as circulating fluid has significant advantages compared to ground source heat pumps if high yielding aquifers are available. Groundwater heat pumps are used in Germany since more than three decades, with strongly growing numbers lately. Apart from heating purposes, groundwater heat pumps can be used also for cooling purposes during the summer time. Closed-loop ground-coupled heat pumps and open-loop indirect groundwater heat pumps are considered to be one of the most energy efficient and environmental friendly air-conditioning systems for temperate zones (Fuji et al., 2007). E.g. Lo Russo et al. (2009) describe an example study for the air-conditioning of a large scale IKEA site in Italy which is run by groundwater heat pumps.

Groundwater heat pumps are frequently termed also as “open loop system” referring to the physical basis of the process. In Germany, groundwater is pumped for heating at an average temperature of 10°C from the aquifer and cooled down to typically 5°C via the heat pump. In most cases the cooled water is re-injected into the aquifer. This is necessary to ensure that there is no lowering of the pumping well temperature by the injection of cold water into the infiltration well. The general concept is displayed in Figure 1.

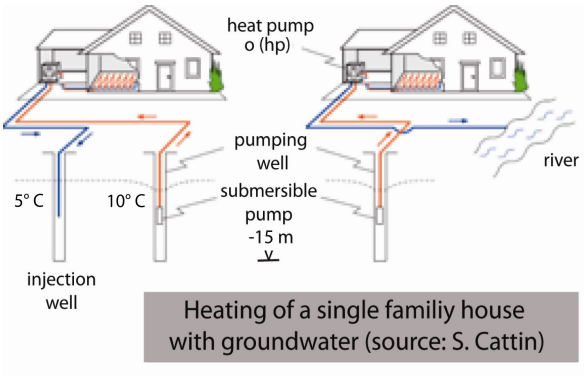


Figure 1: Functional principle of an open loop system.

This concept to supply single households with open loop systems is well established and there are currently more than 700 officially registered groundwater heat pumps in the State of Baden-Württemberg (35 Mio km²). With rising energy costs and the political movement towards increased use of renewable energy sources, the concepts are growing larger. An innovation is now to supply entire districts or housing developments with semi-centralized groundwater heat pump systems. In this system, only a small number of wells are supplying a large number of buildings with groundwater of a constant temperature. In each building, an individual heat pump is installed and the conversion to higher temperature is performed on the spot (Figure 2). In a secondary pipe network, the cold water is collected and conveyed to the injecting wells.

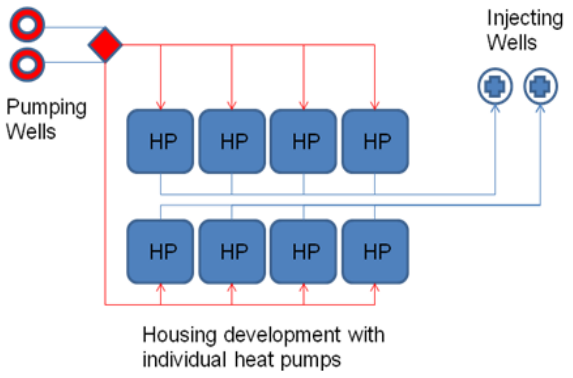


Figure 2: Principle of district heating with open loop systems.

The main advantages of the system compared to the fully decentralized solution are: (i) sensible operation and maintenance of the well system can be performed centrally by experts, and (ii) interference of individual cold water plumes is avoided. The main challenges are (i) construction costs for two additional pipe networks, (ii) high performance wells are necessary for the large flow rates required, and (iii) pronounced drawdown at pumping wells and pronounced groundwater mounding at the injection wells.

A key challenge of this technology is therefore the positioning, design, operation and maintenance of the well system. Optimization may be achieved in terms of reduced environmental impact as well as increased operational efficiency. The following aspects need to be checked before the commissioning of a large scheme:

- Build-up of hydraulic feedback loops/thermal short circuits. A short-circuit is a negative influence of the infiltrated cooled water in the temperature field of the pumping wells which leads to lower efficiency of the entire system
- Changes in water availability of established groundwater users, such as local water works or industrial process water extraction
- Impact on groundwater dependent ecosystems, e.g. drying up of wetlands close to the abstraction wells or habitat changes due to water logging at the infiltration wells
- Impact on built infrastructure: subsidence and compaction or wetting of cellars and basements
- Constraints on geothermal groundwater use of downstream parties
- Hydrochemical problems; e.g. precipitation of iron oxides in the injection well

In order to determine which concepts serve best for specific regional problems, numerical groundwater models are more and more frequently employed. A review of analytical solutions for the problem of thermal-hydraulic feedback has recently been given by Banks (2009).

2. METHODOLOGY

2.1 Analytical Solution

The analytical modeling of temperature fields caused by an infiltration well is based on the arithmetic method by Kobus and Mehlhorn (1980). It supports the solution of shallow geothermal problems. It considers the thermal influence of the covering layer as well as it regards the heat transport only by advection. It is based on the assumption that the relevant aquifer is an ideal type. That means a confined, homogeneous, isotropic and horizontal aquifer with a constant thickness, which includes also a perfect well.

The infiltrating of water in the aquifer causes a plume, which follows the general groundwater flow direction. Kobus and Mehlhorn (1980) describe it by a stream function composed from the inflow velocity of the groundwater and the current of the source (Figure 3). It follows a function to describe the limiting current of an infiltrated, two-dimensional, steady plume.

$$x = \frac{y}{\tan\left(\pi \, \frac{2\pi v_0 m_a}{Q} y\right)} \qquad (1)$$

The expansion of this plume depends on the volume current Q, the inflow velocity of the groundwater υ_0 and the thickness of the aquifer m_a.

From equation 1 follows an equation for the width b_1 of the plume far beyond the well.

$$b_I = \frac{Q}{m_a v_0} \qquad (2)$$

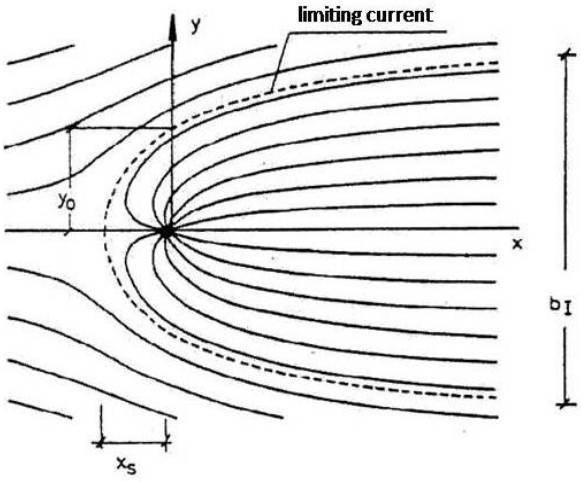


Figure 3: Streamlines and limiting current of a plume in the region of the infiltrating well (Kobus and Mehlhorn, 1980).

For calculating the length of the plume there is a need to know the behavior of the temperature in the plume. It is assumed that the main heat transport happens by the exchange with the atmosphere across the covering layer with a thickness of $_{mc}$. The horizontal heat exchange and the heat transport by dispersion and convection are neglected.

$$n_{eff}\rho_f c_f m_a \left(-\frac{d\Delta T}{dt}\right) = \lambda \frac{\Delta T}{m_c} \qquad (3)$$

The solution of the differential equation is an exponential relationship between the heating of infiltrated water and the retention time t in the aquifer.

$$\Delta T = \Delta T_0 \, e^{-\frac{\lambda}{n_{eff} f c_f m_a m_c} t} \qquad (4)$$

The heating is depended on the effective porosity n_{eff}, the density ρ_f and specific heat of fluid c_f, and the thickness of the aquifer m_a and the covering layer m_c. In the following calculations the density is set to ρ_f = 1000 kg/m³, the specific heat of water to c_f = 4190 J/kg K, the thermal conductivity is set to λ = 2 W/mK.

So there is a required retention time for heating the infiltrated water until the infiltrated water has a certain neglectable temperature difference ΔT to the groundwater. From this required retention time follows a relation to the length of the streamlines by using the stream function.

Through the retention time along the inflow direction the length of the plume can be calculated as

$$t' = x' - \ln(x' + 1). \qquad (5)$$

Where the t' is the dimensionless retention time and x' the dimensionless distance along the inflow direction; with

$$t' = \frac{2\pi v_0^2 m_a}{Q \, n_{eff}} \, t, \qquad x' = \frac{2\pi v_0 \, m_a}{Q} \qquad (6)$$

2.2 Numerical Solution

Combining Darcy´s law with the principles of mass conservation, the general equation of groundwater flow can be derived as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial x} \pm W \quad (7)$$

K, m/s is the hydraulic conductivity in each direction, h, m is the hydraulic potential. The change of mass in the system is just conditional on the change of storage, with S_s, m^{-1} as the specific storage coefficient and the fluid source/sink W.

In order to derive the heat transport equation, the change in heat content of a control volume dV with the surface area dA (with surface normal $\bar{n}$) in a time interval dt is considered. By employing again the principle of energy conservation, the heat transport equation results as:

$$\int_V \left[\frac{\partial}{\partial t}(\rho\, c\, T)\, dV = \int_A \left(\underline{\lambda}\, \nabla T - \rho_f\, c_f\, T\, \vec{v}\right)\right] \vec{n}\, dA + \int_V H\, dV \quad (8)$$

with ρ as density, c as specific heat conductivity and λ as fluid thermal conductivity.

The change of heat content in time is dependent on (i) diffusion, (ii) advection, and (iii) production of heat, with H, Wm^{-3} as the heat production rate.

In the numerical model the heat amount is calculated at every node of the finite element grid. Assuming that the groundwater (T_f) and the rock matrix (T_s) are thermally balanced ($T=T_f=T_s$), thus the equation of the transport system considers the rock matrix as well as the groundwater. The heat amount is calculated as the change of the enthalpy in time, the advective and diffusive heat transport and a source term. The convective term ($\rho_f c_f \bar{v} \nabla T$) is connected to the groundwater flow with the Darcy velocity $\bar{v}$. After Diersch (2005) the diffusion term includes the diffusion as well as the dispersion. To calculate the heat transport it is also necessary to define relevant boundary conditions. These conditions are used for an iterative calculation including all grid elements. Between the grid points the interpolation is linear.

3. CASE STUDIES

3.1 Two-Well Solution (Graben Neudorf)

3.1.1 Setting

The first case study dealt with potential groundwater risks caused by the planned housing district “Hestlich” (Figure 2) which would use groundwater heat pumps for the geothermal supply of the households. The numerical model should simulate the impacts on the groundwater budget of the nearby protection zone and provide optimized well locations (Ulmer, 2008).

The planned housing district is positioned in the southeastern part of the community of Graben-Neudorf, between the cities of Karlsruhe and Speyer (Figure 4). The estate contains an area of 6000 m² with up to 250 apartment units. From this, average demands for warm water the daily pumping and infiltration rates were assumed as at 900 m³/d and simulated accordingly.

The area is part of the Upper Rhine Graben, and lies on a lower terrace of the Graben block which is surrounded by several mountains. The geological setting is given by Quaternary and Pliocene sediments, dominated by sand and gravel with several intercalated horizons of silt and clay acting as hydraulic separation. The pre-quaternary settings consist of Mesozoic and Tertiary sediment rocks divided in several blocks through a number of faults. The sediment filling in the Rhine Graben is divided in several aquifers but only the top aquifer, the “Oberes Kieslager” is of concern in the model building process. The average hydraulic conductivity is specified with $2.7x10^{-3}$ m/s, in the relevant modeling area the average conductivity is specified with $2.0x10^{-3}$ m/s upon a limited database review.

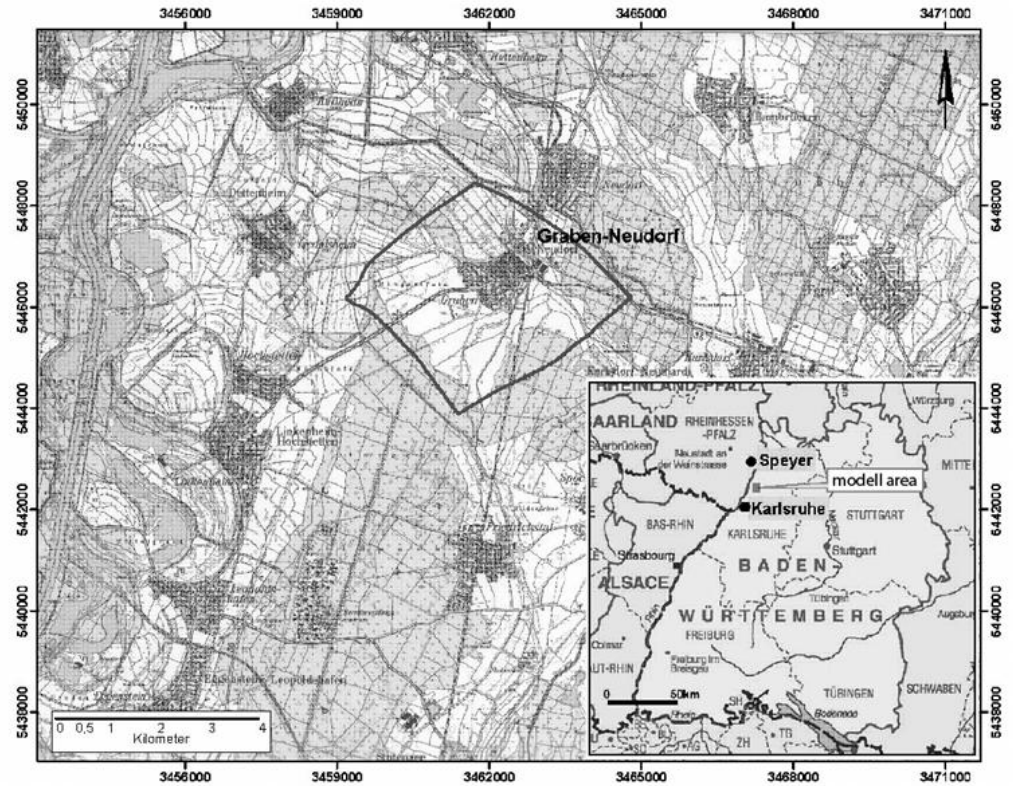


Figure 4: The model area between Karlsruhe and Speyer (source: LVA, 1982).

The size of the model is about 14 km^2. The upstream flow boundary condition is a fixed head following the isolines of the groundwater table constructed by the state environmental agency for representative conditions. The downstream model boundary is the fixed head potential of the river Rhine, which is effectively draining the entire area. In addition, two small creeks are running through the area, thus providing the possibility for both infiltration and exfiltration of surface water. These are implemented with a head –dependant Cauchy boundary condition (or "transfer"-boundary condition). The wells in the housing district are implemented as boundary condition of the fourth kind.

The hydrogeological situation is represented by a two layer configuration for stationary flow and later on increased to ten layers in order to obtain a better vertical discretisation. Based on an existing database of pumping tests results, hydraulic conductivities were assigned in polygons for each layer. During the calibration process the hydraulic conductivities were varied in order to achieve the best fit between measured and calculated groundwater heads. The average difference at the selected observation wells was 0.08 m.

In order to simulate the geothermal heat supply, two wells were implemented. The maximum pumping rate considered was 900 m³/d. For the groundwater flow model most scenarios were computed as steady state l. The distance between the pumping well and the corresponding infiltration well is given as ca. 400 m.

The heat transport is computed transient, which means, that the pumping rate will vary during the seasons. In addition to the flow model, the effective porosity, the volumetric heat capacity, the thermal conductivity, the dispersivity and the groundwater temperature were specified. A constant groundwater temperature of 11°C was implemented at the upstream model boundary as a first type (Dirichlet) boundary condition At the injection well a temperature of 5°C is assumed. This is the lowest possible degree allowed by the local regulators.

3.1.2 Results of Analytical Modeling

For the analytical modeling, a constant pumping rate of 900 m³/d with a temperature difference of 6°K between the injected water and the ambient groundwater was used. The thickness of the aquifer is set by m_a = 25 m and the covering layer is m_c = 2 m, the effective porosity is 15% and the inflow velocity is 6x10^{-6} m/s.

The analytical solution yields as a result that the temperature difference between injected is reduced to 3°K in a distance of 587 meters from the injection well. The numerical solution implies a length of ca. 400 meters, resulting in a fair congruence.

The main factors for differences between the analytical and the numerical solutions are:

- The exchange with the atmosphere is not taken into account in the numerical model
- The analytical model does not assume the horizontal heat exchange
- The numerical model regards the heat transfer by dispersion
- Vertical placement of the injection: in the analytical solution a perfect well is assumed, in the numerical model finer discretisations with cold water injection over only short intervals are possible
- Growing influence of dispersion and convection. (In the calculations of Kobus and Mehlhorn the thickness of the aquifer is not larger than 20 meters.)

3.1.3 Results of Numerical Modeling

The positioning of the wells has shown that neither of them is in the direct area of influence of the other one. Furthermore, the drinking water wells nearby are also not influenced.. The drawdown, respectively the rise of the groundwater is very low with 0.08 cm, and at the border of the reserve area about 0.01 cm. Thus, no negative impacts for the reserve areas are expected, even in the case of moderately higher pumping rates.

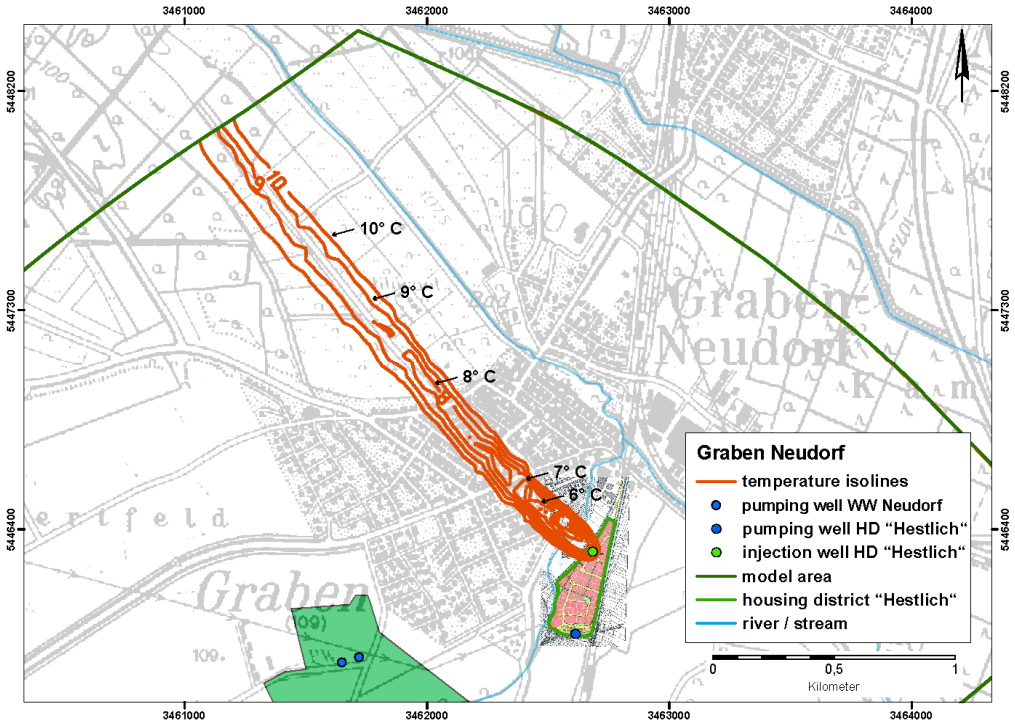


Figure 5: The simulated changes of the groundwater temperature due to the geothermal use.

Based on the results of the groundwater flow model and the boundary conditions the simulation time was implemented at 7300 days. Figure 5 shows the simulated temperature field.

It shows that the thermal influence area is limited to the downstream flow of the infiltration well. The position of the wells avoids a hydraulic short-circuit, and no temperature changes in the pumping well will take place. Furthermore, no thermal influences will probably occur in the water protection zone.

3.2 Multi Well Solution (March Hugstetten)

3.2.1 Setting

The Second Case Study also started with a numerical model to predict the influence on the water budget of a biological reserve area which lies very close to the planned housing district "Neumatten". This housing disctrict in the Community of March-Hugstetten, is located in the so called Freiburger Bucht, a region between the Kaiserstuhl and the Black Forest. It lies in an area with protected landscapes and agriculturally used land. The district contains 151 apartment units within a total area of 16.800 m². The specific thermal heating demand is calculated between 57 and 71 kWh/m²a, the specific heating demand for the warm water usage from 9 to 14 kWh/m²a, thus results in a total heating demand of 1260 MWh/a.

The hydrogeological parameters are typical for the region. The topmost aquifers consist mainly of unconsolidated Quaternary sediments. The older underground is built-on Mesozoic and Tertiary rocks which are fractured in a number of blocks. The sediment fillings of the Freiburger Bucht are subdivided in 6 units, but for the use in the model only two units are of concern, the Neuenburg and the Breisgau formation are the main aquifer in the relevant area.

3.2.2 Numerical Modeling

Consequently only two layers are specified in the numerical 3 D model. The top is defined by the characteristics of the Neuenburg formation and the base of the characteristics of the Breisgau formation. In order to represent the geology, information from existing base isoline plans were transferred to a geographical information system und subsequently imported into FEFLOW. The dimension of the model is roundabout 10 km². Boundary conditions were specified as fixed head (first order) at upstream and downstream borders. In addition the river Dreisam was implemented with a third type (Cauchy) boundary condition. In the status quo scenario, also the wells from the local water works were represented with fourth type boundary conditions. The default hydraulic characteristics specified by the Landesanstalt für Umweltschutz Baden-Württemberg were used as initial values for the calibration process. After more than 20 manual iterations it was possible to calibrate the model adequately by adjusting the hydraulic conductivity (Hötzl et al., 2007). The average difference between real and simulated values could be established at 0.13 m.

The geothermal open loop system was intensively discussed with the commissioning engineers. Different alternatives were considered:

1. Discharging of the cold water into a small surface water creek
2. Infiltration of the cold water via a series of infiltration ditches
3. Infiltration of the cold water via a series of injection wells

Option 1 was quickly discarded since it would result in a serious disturbance of the local groundwater balance and a drying of the nearby wetland biotope. Furthermore, the discharge of 5° cold water into a creek will significantly change the aquatic fauna.

Option 2 was attractive since the construction of the ditches requires lower investment. However, after some percussion drilling and an on-site infiltration test, the silty overbank fines which dominate the first 3 meters of the soil profile effectively prohibited the required infiltration of at typically 1200 m³/d.

Option 3, which was then also realized, was the only feasible solution remaining and explored in detail with the numerical model. 7 wells are used for pumping while 12 wells are used for injection (Figure 6). Three different pumping rates were considered. At first the real proclaimed rate of 1200 m³/d and two further more conservative rates with 2400 m³/d and 3600 m³/d (worst case). Heat transport modeling was performed in transient mode, thereby reflecting the different energy requirements in each month. This can be a critical issue since the low water abstractions in the summer time lead to a restoration of the natural temperature field before the next winter season. Different numerical solutions such as full upwinding and the standard Galerkin method were compared in their sensitivity to numerical dispersion. Model runtime was set to 3650 days (10 years) with an adaptive time step control. The maximum time step was given as on month, reflecting the monthly changes in abstraction rates.

The simulation of the heat transport were based on the condition that the groundwater temperature is constantly 10°C, this is the annual average value in this region. Therefore the simulations started with an initial extraction temperature of 10°C. The minimum infiltration temperature is fixed with 5°C (worst case parameter) and it should not go below this value. The simulation runs showed that the temperature at the pumping wells decreased during the process below 9.5°C, indicating a hydraulic and geothermal short circuit for some of the wells. This scenario is of course detrimental for the efficiency of the open loop system and required to change the well positions. The optimization process was considering five goals:

- Reduce pumping of cold water from the injection wells. Preserve a minimum ΔK of 4°K between pumping and injection.
- Avoid any drop in groundwater level at the biotope natural reserve area
- Avoid excessive groundwater table mounding
- Stay within the purchased ground for the housing development
- Avoid interference with the local water works in about 1 km distance

Given these constraints, it was impossible to avoid any hydraulic short circuit for all wells. The results have shown that under the implemented boundary conditions and parameters the temperature will probably decrease about 1.7°C to a minimum groundwater temperature of 8.3°C in the northwestern area, the lowest temperature decrease can be found in the southwestern well with 9.9°C (Figure 6). An establishment of equilibrium is achieved after 2.7 years. After several alternative positioning scenarios of the wells it was possible to reach an average water temperature of

9.5°C if the water abstracted from all 7 wells is mixed before the supply to the households. It must be said of course, that this is the result of a pure forward modeling exercise, thus a significant uncertainty remains. A regular monitoring program is therefore recommended.

With regard to the biotope reserve area, all groundwater flow simulations have shown that the usage of groundwater by the housing disctrict will have little or insignificant negative impacts on the nearby reserve area. The infiltration results rather in an increase of the groundwater table. Due to the balanced pumping and injection the impacts on the groundwater table are only local, the groundwater budget itself in not influenced.

3.2.3 Analytical Modeling

As the analytical arithmetic method by Kobus and Mehlhorn (1980) does not include a multiple well solution, an approach with one big infiltration well in the middle of the field was tested. So there was a pumping rate of 7x1200 m³/d with a temperature difference of 5°K. There was taken averaged values for all necessary parameters of the ground. The thickness of the aquifer is set by m_a = 20m and the covering layer m_c = 2m, the effective porosity is 25% and the inflow velocity is $2.5x10^{-6}$ m/s.

The analytical solution yields to a length of the plume with 700 meters with a temperature difference of 1°K. By measuring the plume of the numerical model from the same set, there is a length of 890 meters. The magnitudes of both solutions are the same. The analytical calculated length of the plume is shorter than the numerical solution because the heat transport by dispersion is not considered (Kobus and Mehlhorn, 1979). So the analytical arithmetic method is suitable for a first estimate.

The analytical method is misleading for calculation of the width. It is 1950 meters. The reason is the great volume current of the superposition of the infiltration rates compared with the inflow velocity.

3.3 Seasonally Changing Systems (Rastatt)

In a further case study located in Rastatt (SW-Germany), we calculated the impact of seasonally inversed pumping and injection activities. During summer time, the groundwater heat pumps are used for cooling purposes. In this period, water with a temperature of 20°C is injected into the upstream wells, thus building up a plume of groundwater with elevated temperature. In winter time, the orientation of the well system is inversed. The summer time injecting well now turns into a pumping well. In terms of efficiency this is very attractive, since a large ΔK can be used. At the beginning of the winter, the maximum ΔK would be around 15°K and it takes almost the complete winter to decrease to the natural background ΔK of 5°K (Figure 7).

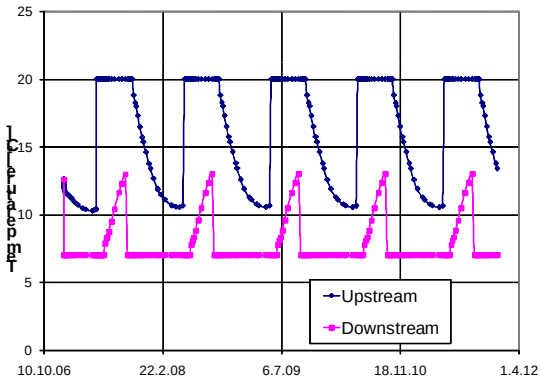


Figure 7: Simulated groundwater temperature at seasonally changing pumping and injecting wells.

The modeling exercises showed the utilization of the aquifer for heat storage to increase efficiency of the open loop system. However, a technical scheme with reversible flow direction is currently too costly and also the environmental regulators raise concern about the injection of warm water into aquifers.

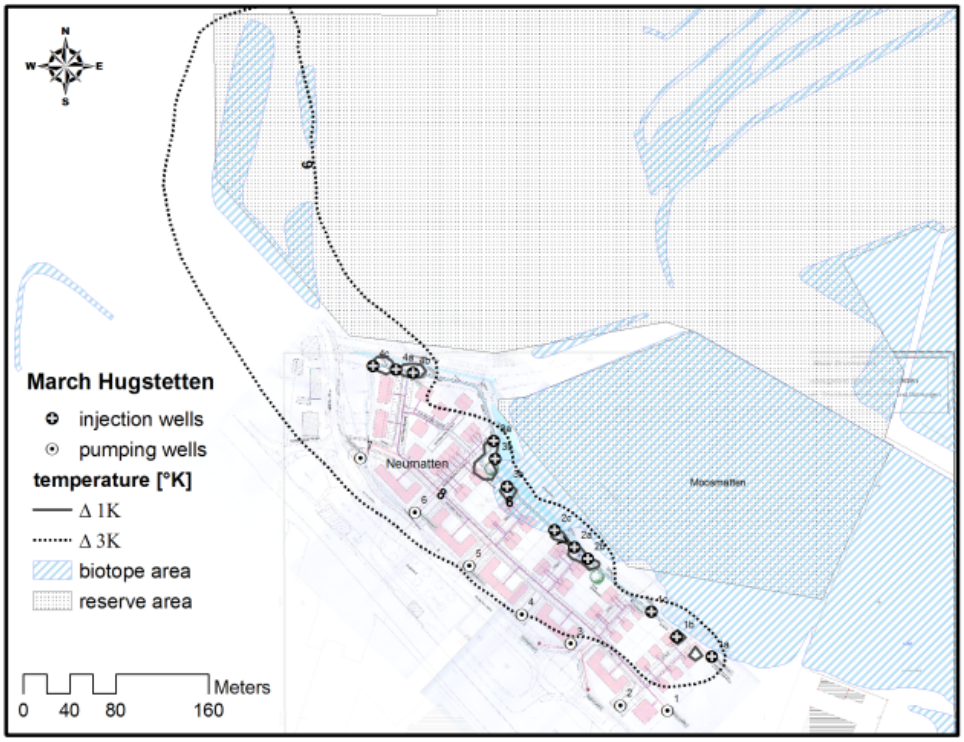


Figure 6: The location the wells in the housing estate and the nearby reserve area.

4. CONCLUSION

Semi-decentralized solutions for groundwater heat pumps offer a promising solution to the problem of mutual pumping scheme interference of single households and enable a larger scale use of this technology which easily surpasses conventional ground source heat pumps in terms of COP (coefficient of performance). However, for larger scale groundwater heat pumps or open loops systems the environmental impact of such schemes needs to be assessed. This assessment can effectively be done with numerical groundwater models which also offer the possibility to optimize the system performance by reducing hydraulic short circuits. The analytical solution by Kobus and Mehlhorn (1980) for the length of a cold water plume offers a reasonable alternative to the numerical model, albeit mainly in terms of calculating plume lengths. The optimization was performed with the goals of (i) minimizing cold water impact on the pumping wells, (ii) minimizing interference with the water budget of nearby groundwater protection zones. The transient simulations have shown the advantage of implementing seasonal changes in the abstraction and injection regimes, thus addressing the thermal recovery of the aquifer system in times of low heat demand. From the viewpoint of energy efficiency an open loop system with heating and cooling purpose is best operated with seasonally changing well functions, therefore utilisizing the warm water stored in the aquifer during summer in the heating period in winter.

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