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Thermal groundwater utilization at the new campus of the Vienna University of Economics and Business - modelling and experience after 10 years of operation

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ABSTRACT: In recent years, geothermal energy systems have been increasingly used to cover heating and/or cooling requirements. Open systems such as direct groundwater utilization can be used to generate geothermal energy. The groundwater is extracted via extraction wells, heated in a chiller or cooled in a heat pump and then fed back into the aquifer via recharge wells.

There are no closed analytical calculation methods for calculating the extent of the temperature changes caused by the infiltration of heated or cooled water into the groundwater that can take all thermal and hydraulic processes into account. For smaller systems, for example, the *Ingerle* method can be used to estimate the extent of the thermal front. For more complex systems numerical modeling for coupled calculation of thermal and hydraulic problems must be applied.

These thermal and hydraulic calculations are demonstrated using one of the largest projects realized in Vienna. The new campus of the Vienna University of Economics and Business, which was completed in 2013, has a system for the direct use of groundwater for heating and cooling with a pumping capacity of up to 150 l/s. Water is extracted via a horizontal filter well consisting of 10 horizontal filter strings; the water is returned via seepage trenches and three recharge wells, which influence the groundwater up to a distance of 700 m. The installed system can achieve an annual heating work of approx. 2,500 MWh and an annual cooling work of approx. 5,700 MWh, a heating capacity of approx. 2.5 MW and a cooling capacity of approx. 3.2 MW. The proportion of heating and cooling from groundwater amounts to around 65 to 70 percent of the campus' total consumption. After a 10-year operating phase, the planning assumptions can now be compared with the actual energy data.

KEYWORDS: Thermal groundwater utilization, geothermal energy, green building, horizontal filter well.

1 INTRODUCTION

Groundwater has a relatively constant temperature throughout the year. It is therefore very well suited for thermal use. This essentially requires groundwater extraction points (e.g., vertical filter wells) and groundwater return points (e.g., recharge wells). In heating mode, groundwater is extracted at the extraction point and heat is extracted from it. The cooled water is then returned to the groundwater at the return point. In cooling mode, heat is added to the extracted groundwater and the heated water is infiltrated again at the return point.

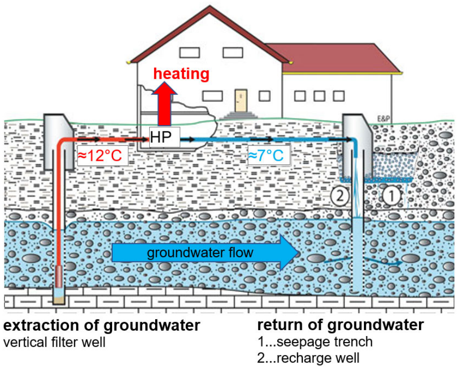

Figure 1. Schematic diagram of direct thermal groundwater utilization for heating purposes (Baudirektion Kanton Zürich, 2010)-adapted.

The new campus of the Vienna University of Economics and Business (WU Campus) has been equipped with a system for the direct use of groundwater for heating and cooling purposes. This "green building" project represents the largest such use in an inner-city area in Austria (Adam, et al., 2016).

2 THERMAL GROUNDWATER UTILIZATION AT THE WU CAMPUS

2.1 *Project data*

The new WU Campus covers an area of approximately 90,000 m² and comprises six building complexes (see Figure 4) with a built-up area of 35,000 m² and an effective area of approx. 100,000 m². Construction began in 2009, and since the winter semester of 2013, the WU Campus has provided space for 25,000 students and 3000 workplaces. The client was the project company "Wirtschaftsuniversität Wien Neu GmbH" (Bundesimmobiliengesellschaft m.b.H. + Vienna University of Economics and Business).

2.2 *Ecological, holistic energy concept*

The WU Campus was designed and built as a green building and has been awarded the ÖGNI certificate. Around two-thirds of the energy required for heating and cooling is generated through the use of groundwater. Three heating and cooling machines are used in winter to heat the building and in summer to cover peak cooling energy requirements. Because the buildings are primarily cooled and heated via thermo-active building systems, the groundwater can be used directly for cooling in summer (Gary, 2015).

The buildings are primarily supplied with cooling/heating capacity of around 2.5 to 3 MW through the thermal use of groundwater. The proportion of heat and cooling obtained from groundwater accounts for around 65 to 70% of total consumption. For cooling, the groundwater is used directly, separated from the hydraulic system only by a heat exchanger. This is possible because the thermo-active building systems and the cooling ceilings can be operated at correspondingly high temperature levels (approx. 14°C). Cooling therefore only requires electricity to operate the pumps, which means that cooling is provided extremely efficiently. Thermo-active building systems also offer advantages in terms of heating, as the low flow temperatures of around 30°C can be generated by the heat pumps with a high degree of efficiency (Gary, 2015).

Compression cooling machines with recoolers are used to cover peak loads. These are also used as heat pumps for heating, thus serving a dual purpose. In addition to groundwater, the waste heat from the data centers also serves as an energy source for the heat pumps. In order to avoid having to work with "very cold" cold water throughout the entire site, decentralized compression chillers are used for dehumidification in the ventilation systems of each building. This eliminates the risk of condensation. Decentralized room air dehumidification eliminates the need to run the cold water pipe at 6°C, as it is currently common practice. This method has particular advantages in a large site such as the WU campus, as losses are correspondingly higher with very cold water (Gary, 2015).

2.3 *Heating/cooling energy and pumping rate for thermal groundwater utilization*

Based on the estimated total energy demand for the WU campus, the planner first determined the proportion of capacity as well as energy that should be covered by groundwater. The COP of the heat pumps/chillers is already taken into account in the data in Figure 2.

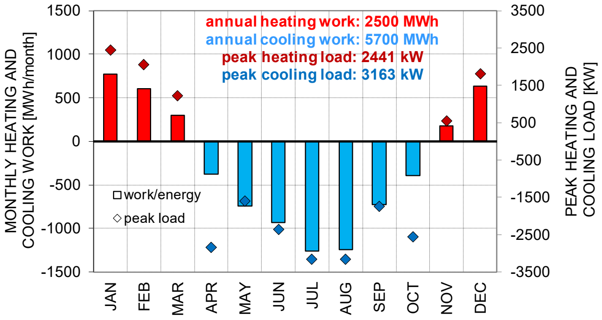

Figure 2. Planned heating and cooling work as well as heating and cooling load to be provided by thermal groundwater utilization.

The required (hourly) groundwater pumping rate was calculated based on the (hourly) energy demand. An average groundwater extraction temperature of 12°C (based on groundwater temperature measurements) and a groundwater return temperature of 7°C (heating case) or 17°C (cooling case) were assumed, resulting in a planned temperature change of $\Delta T = \pm 5$ K. As an example, a required pumping rate of 150 l/s is required to cover the peak cooling load of 3163 kW:

$$\dot{Q} = c \cdot \dot{m} \cdot \Delta T = c \cdot \rho \cdot \dot{V} \cdot \Delta T \qquad (1)$$

$$\dot{V} = \frac{\dot{Q}}{c \cdot \rho \cdot \Delta T} = \frac{3163 \cdot 1000}{4200 \cdot 1000 \cdot 5} = 150\ l/s \qquad (2)$$

Figure 3 illustrates the required pumping rate for thermal groundwater utilization over the course of a year. The maximum pumping rate is 150 l/s and is required continuously for 11 hours during a day in the summer months (peak load coverage). The pumping rate is then reduced (base load coverage) so that the maximum daily average pumping rate is 104 l/s. The average pumping rate per month varies between 11 and 80 l/s, and the average annual pumping rate is 44 l/s.

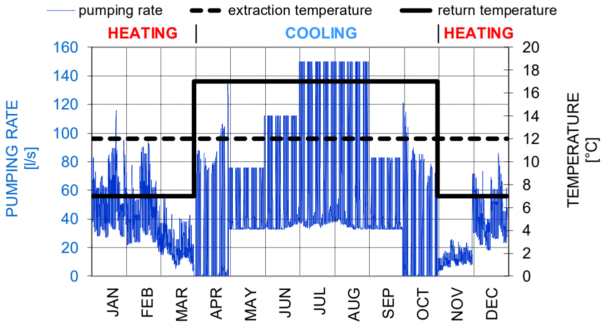

Figure 3. Planned pumping rate, groundwater extraction and return temperatures over the course of one year.

2.4 *Thermal groundwater utilization system*

A horizontal filter well was planned and ultimately constructed for groundwater extraction (see also section 4.1). Groundwater is extracted via this well and either cooled (for heating purposes) or heated (for cooling purposes) in the technical room. The groundwater is then returned to the aquifer on the downstream side at the opposite property boundary via seepage trenches and three recharge wells (see Figure 4).

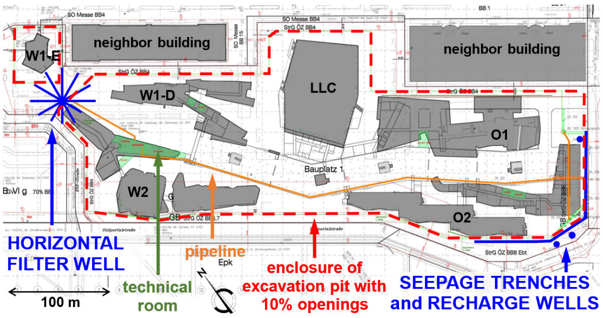

Figure 4. Groundwater extraction (horizontal filter well) and groundwater recharge system (seepage trenches and three recharge wells) at the WU campus (Vasko+Partner Ingenieure, 2008)-adapted.

2.5 *Subsurface and groundwater conditions*

The subsoil stratification was explored in the campus area with a total of 18 boreholes and is as follows (values in brackets indicate layer thickness):

- Top layer of heterogeneous fill (1.0 – 3.8 m)
- Alluvial sand and loam (0.0 – 4.9 m)
- Danube gravels (2.2 – 10.4 m): aquifer
- Tertiary fine sands in some areas (0.4 – 1.35 m)
- Vienna Tegel – tertiary silts and fine sands: aquitard at a depth of approx. 5.4 to 10.9 m

The free groundwater is located within the Danube gravels; based on a nearby long-term groundwater measuring station, it was found that the average groundwater level is t = 4.26 m below ground level. The aquifer thickness, relevant for thermal groundwater utilization, was thus approx. H = 7 m. Figure 5 illustrates the layer structure for subsequent modeling.

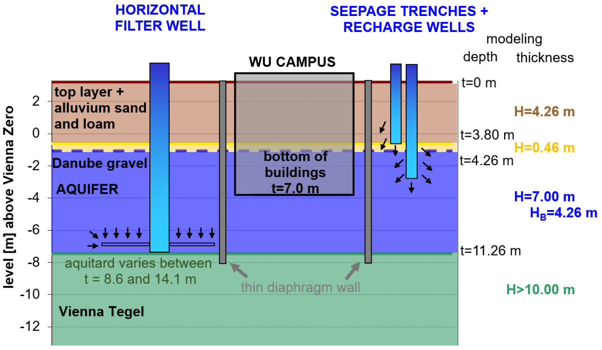

Figure 5. Subsurface profile for modeling.

Figure 5 also illustrates the buildings with the basements in the aquifer. The depth of the basements of the six building complexes varies slightly; the average bottom of the basements is at a depth of t = 7 m. The aquifer thickness below the buildings is therefore reduced to $H_B = 4.26$ m.

2.6 *Special project constraints*

2.6.1 *Enclosure and waterproofing of excavation pit*

To seal the excavation pits (building W1E and buildings W1-D, W2, LLC, O1, and O2), thin diaphragm walls (vibrating beam slurry walls) were constructed. In order to restore groundwater communication after the building objects had been constructed, around 10% of the thin diaphragm walls were reopened. These openings were created using the jet grouting method (simplex method with high-pressure water jet).

2.6.2 *Artificial groundwater management in the project area*

The WU Campus is located between the Danube and the Danube Canal, in Vienna's 2nd and 20th districts. Within this area, the groundwater is artificially supplemented and managed with water from the Danube. The reason for this is that the construction of the Freudenau hydro power plant (HPP, completed in 1998) caused the Danube to be dammed to a level that is higher than the ground level of Vienna's 2nd and 20th districts. Dams with impermeable walls were therefore built. In order to regulate the groundwater conditions in the 2nd and 20th districts in such a way that there is no significant quantitative change in the groundwater conditions and no deterioration in groundwater quality as a result of the damming, an artificial groundwater management system is operated. The groundwater is artificially supplemented with water from the Danube by pumping over the impermeable walls constructed along the right bank of the Danube.

This groundwater supply is provided by 21 pairs of wells (one extraction well on the Danube side and one recharge well on the landward side of the impermeable wall), which are spaced 100 to 600 m apart over a length of 13 km and controlled by around 160 water level measuring points.

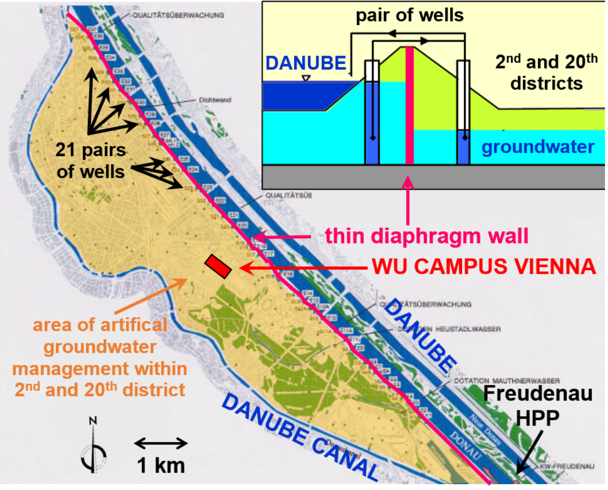

Figure 6. Location of the 21 pairs of wells along the impermeable wall (thin diaphragm wall) on the right bank of the Danube for groundwater management (Dreher & Gunatilaka, 1997). The location of the WU campus is also shown. Top right: Cross-section of the dammed Danube and the pair of wells for bridging the impermeable wall and supplying groundwater (Dreher, et al., 2002).

3 HYDRAULIC AND THERMAL MODELING AND SIMULATION

3.1 *Modeling concept*

To calculate the hydraulic and thermal effects of the planned thermal groundwater utilization, two simulation models were created using the FEM software *Comsol Multiphysics*:

2D-model "hydraulic simulation": The focus of this model is on calculating hydraulic changes based on groundwater extraction/recharge and the associated flow conditions. Due to a model developed by *Stanford University* (Kitanidis, 2008) (Chui & Freyberg, 2007), it is possible to simulate three-dimensional conditions (distribution of hydraulic head in the plan view) using a two-dimensional calculation model. Instead of permeability k_f [m/s], the so-called transmissivity T [m²/s] is used for the calculation. This represents the integral of the k_f value over the water-filled thickness H [m] of the aquifer. In the simulation, the water-filled thickness represents the hydraulic head varying at each point, which means that transmissivity is also a model variable according to which the equation matrix is ultimately solved. This allows the hydraulic head to be specified for each point and thus also the drawdown or heightening funnel in the area of groundwater extraction or recharge.

3D-model "thermal simulation": To investigate the thermal influence area of the planned groundwater use, a three-dimensional FEM model was developed in which temperature propagation is calculated over a period of 20 years, taking into account the hydraulic boundary conditions. Since the focus of this three-dimensional model is on calculating the thermal range of the thermal groundwater use, a constant groundwater thickness is assumed in the model area and it is assumed that this layer (Danube gravel) is completely water-saturated at all times. For this reason, the model is based on the *Laplace* equation (with *Darcy's* law).

3.2 *Hydraulic and thermal soil parameters*

The following soil parameters were derived for the hydraulic calculations based on available subsurface data and empirical values:

- Top layer incl. alluvial sand and loam: permeability $k_f = 1 \cdot 10^{-9}$ m/s; porosity $n = 0.44$; density $\rho = 1760$ kg/m³
- Danube gravel: $k_f = 2.5 \cdot 10^{-3}$ m/s; $n = 0.25$; $\rho = 2000$ kg/m³
- Vienna Tegel: $k_f = 1 \cdot 10^{-10}$ m/s; $n = 0.43$; $\rho = 2000$ kg/m³

To take natural groundwater flow into account, it is necessary to calculate the filter velocity v_f. With a groundwater level gradient of $i = 40$ cm per 1 km (equivalent to 0.4‰), this results in:

$$v_f = k_f \cdot i = 2.5 \cdot 10^{-3} \cdot 0.0004 = 1 \cdot 10^{-6}\, m/s \tag{3}$$

The groundwater flow direction was assumed to be from the Danube toward the Danube Canal (north to south, which represents the flow direction at medium groundwater levels).

The thermal soil parameters were derived partly from (VDI Verein Deutscher Ingenieure e.V., 2008) and partly from empirical values. It should be noted that the literature primarily contains thermal parameters on soils as a whole, but for the FEM calculations the total soil matrix had to be split into a solid fraction and a water fraction. This is necessary because water movement (groundwater flow) must be taken into account within the aquifer and a distinction must be made between the solid fraction and the water fraction for the calculation of the individual heat transport processes. The relationship between the total soil matrix and the solid fraction (index s) and water fraction (index w) is reflected in the following equations for specific heat capacity c_p and heat conduction λ:

$$c_{Matrix} = \frac{n_w \cdot \rho_w \cdot c_{p,w} + n_s \cdot \rho_s \cdot c_{p,s}}{n_w + n_s} \tag{4}$$

$$\lambda_{Matrix} = \frac{n_w \cdot \lambda_w + n_s \cdot \lambda_s}{n_w + n_s} \tag{5}$$

The following table shows the estimated values.

Table 1. Thermal soil parameters for the model calculations.

	fraction [%]	heat capacity c_p [J/kg/K]	density ρ [kg/m³]	heat conductivity λ [W/m/K]
top layer (matrix)	100	1136	1760	1.8
Danube gravel (solid fraction)	81	987	2000	2.1
Danube gravel (water fraction)	19	4217	1000	0.6
Vienna Tegel (matrix)	100	1100	2000	1.8
concrete (matrix)	100	1000	2400	1.8

3.3 *2D-model "hydraulic simulation"*

Based on the theoretical model approaches described in section 3.1, a hydraulic simulation of the horizontal filter well and the seepage trenches with the three recharge wells (see Figure 4) was carried out. In an initial modeling phase (project submission phase), simplified model approaches were chosen, assuming, among other things, an averaged building bottom and constant permeability throughout the model area. In a second modeling phase, the individual building bottoms (varying from $t = -4.3$ to -7.0 m) were modeled exactly by setting the individual water-filled thickness H_B beneath each building.

It was also taken into account that the permeability below the buildings was changed as a result of the foundation measures carried out: for building parts without foundation measures, a permeability of $k_f = 5 \cdot 10^{-3}$ m/s was used, for buildings with vibrocompaction $k_{f,V} = 5 \cdot 10^{-4}$ m/s, and for those with pile foundations $k_{f,P} = 2{,}5 \cdot 10^{-3}$ m/s (see Figure 8).

Furthermore, the excavation pit enclosure (thin diaphragm wall), including the subsequently created openings for groundwater communication, was also precisely modeled. To take cumulative effects into account, the infiltration systems for roof drainage (rainfall events) were also modeled and taken into consideration (Figure 8).

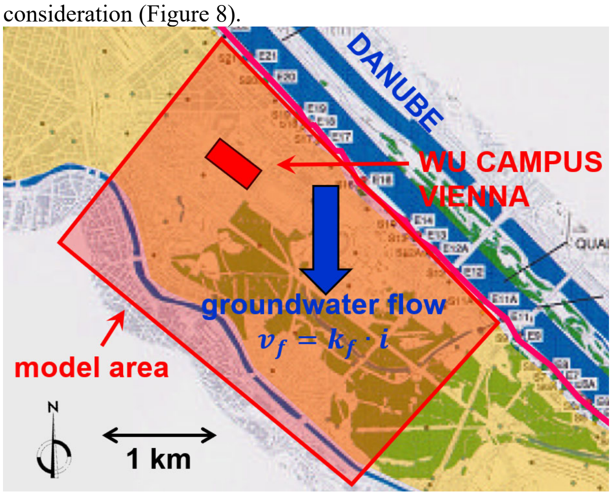

Figure 7. Model area for the simulations (see Figure 6) with the location of the WU campus and the assumed groundwater flow direction.

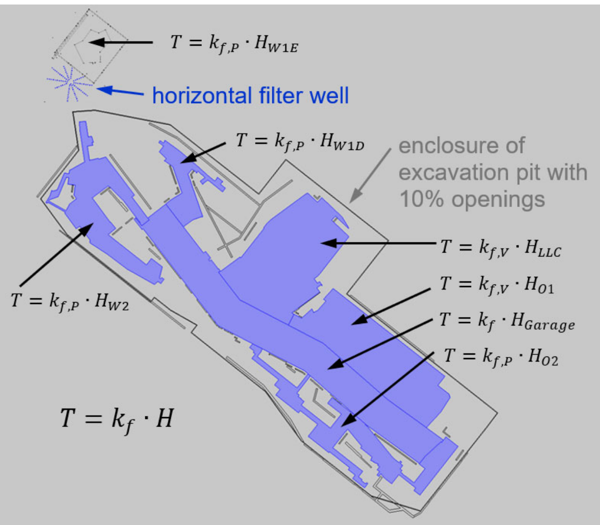

Figure 8. Cutout of the model with WU campus. The basement of the buildings are marked in blue; in addition, the transmissivities T used in the hydraulic model to take into account the different foundation measures and individual water-filled thickness H_B beneath each building are indicated.

The key aspects of the hydraulic model can be summarized as follows:

- Stationary calculations using the average annual pumping rate (44 l/s) and the maximum average monthly pumping rate (80 l/s)
- Different aquifer properties (groundwater thickness and permeability) depending on building depth and foundation measures
- Artificial groundwater management (see section 2.6.2) is indirectly taken into account via filter velocity v_f (flow direction, permeability, gradient see section 3.2)
- Horizontal filter well, seepage trenches and recharge wells are modeled precisely
- The geometry of the structure, including the thin diaphragm wall and its openings, is taken into account
- Cumulative effects can be taken into account (rainfall events, neighboring water rights)

Figure 9 shows an example of the calculation result for a pumping rate of 80 l/s without cumulative effects.

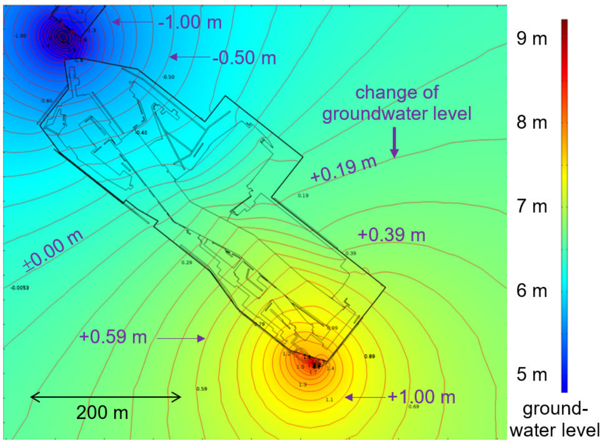

Figure 9. Result of the hydraulic simulation: groundwater level (initial state H = 7 m) and change in groundwater level as a result of the extraction and return of groundwater due thermal groundwater use at a pumping rate of 80 l/s (stationary solution).

3.4 *3D-model "thermal simulation"*

There are no closed analytical calculation methods that describe all thermal and hydraulic processes for calculating temperature changes caused by the recharge of heated or cooled groundwater. However, for smaller systems, the *Ingerle* method (ÖWAV, 2009) can be used to estimate the thermal influence zone (temperature change of >1 K compared to uninfluenced groundwater).

However, for more complex systems with multiple wells, high pumping rates, or complex subsurface and construction conditions, three-dimensional modeling with numerical simulation programs (e.g., *Comsol Multiphysics*) must be used, which allow a coupled calculation of thermal and hydraulic tasks. By this the thermal influence zone in the groundwater recharge area can be calculated. The most important heat processes in the ground are: heat conduction, heat flow (convection), dispersion and heat storage.

The key aspects of the thermal model can be summarized as follows:

- Transient calculation for a period of 20 years
- Time step interval of 1 month
- Calculation using average monthly pumping rates (max: 80 l/s, min: 11.7 l/s)
- Constant aquifer properties for the entire model area (groundwater thickness, flow direction, permeability, porosity, gradient)

- Artificial groundwater management (see section 2.6.2) is indirectly taken into account via filter velocity v_f
- Extensive extraction or infiltration of groundwater
- Geometry of the structure (average depth of basements), including the thin diaphragm wall and its openings, are taken into account

Figure 10 shows the groundwater temperature changes due the thermal groundwater utilization, as calculated by the coupled hydraulic-thermal simulation. The range of thermal influence extends approx. 700 m from the recharge point; a slight short-circuiting effect can also be seen, whereby thermally altered groundwater is re-drawn through the horizontal filter well.

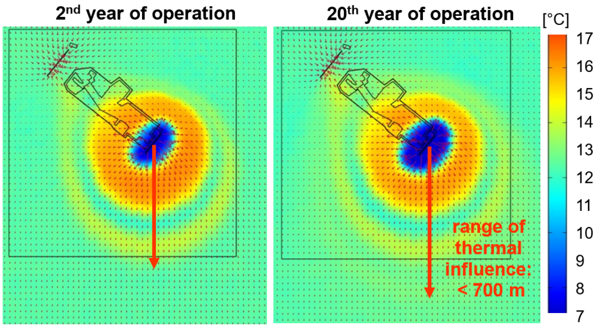

Figure 10. Determination of the range of thermal influence due the thermal groundwater use (plan view). During the heating period, water at a temperature of 7°C is returned to the aquifer at the recharge point, and during the cooling period, water at a temperature of 17°C is returned. The undisturbed groundwater temperature is 12°C.

3.5 *Hydraulic and thermal influence range*

In order to assess the impact on existing water rights, a simulation calculation was also carried out in which, in addition to groundwater use by the WU Campus, all other (third-party) groundwater uses were also modeled (cumulative analysis). For this purpose, data on all existing water rights in the surrounding area was collected and the maximum permitted pumping rates were applied in the model.

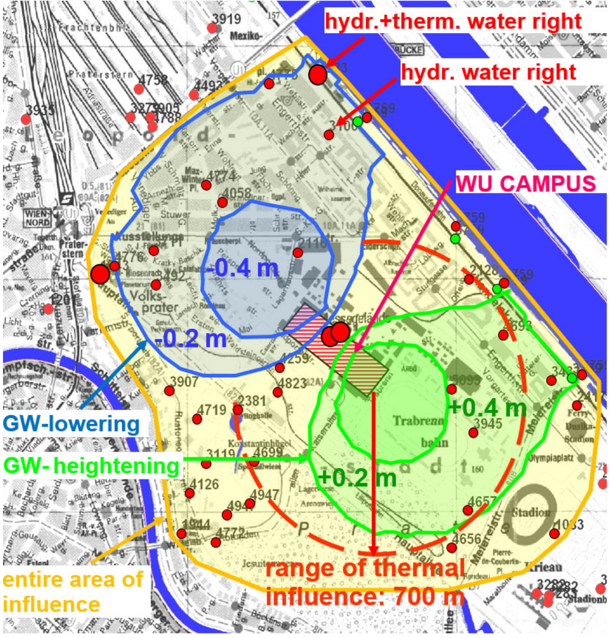

Figure 11. Hydraulic (blue: lowering; green: heightening) and thermal (red dotted line; 700 m) areas of influence as well as existing hydraulic (red dots) and existing hydraulic+thermal (large red dots) water rights within the entire area of influence (yellow area).

These hydraulic model calculations, together with the thermal calculations, ultimately formed the basis for assessing whether the numerous water rights existing in the surrounding area would be affected by the operation of the groundwater utilization plant (Figure 11). The review of each individual water right (41 hydraulic and three hydraulic+thermal uses) ultimately showed that, although the groundwater use by the WU Campus does affect third-party water rights, the consensual use of all water rights can continue.

It should also be mentioned that, in addition to this evaluation of water rights, a geotechnical assessment was also carried out, in which all buildings in the hydraulic influence area were taken into consideration to determine whether any adverse effects (e.g., settlement, flooding) were to be expected.

It should also be mentioned that the artificial groundwater management system in the 2nd and 20th districts is used (by adjusting the pumping times) to keep changes of groundwater level within the influence area as low as possible.

4 CONSTRUCTION PHASE

4.1 *Horizontal filter well*

The described horizontal filter well for groundwater extraction is located between buildings W1E and W2 (see Figure 4). The shaft, which is approximately 9 m deep and has an internal diameter of 2.8 m, was constructed using the sinking method; The horizontal filter strings were constructed using the *Ranney-Falley* method with thick-walled slotted filter pipes (DN200, single slotted holes 6x35 mm made of stainless steel). A thick-walled desanding rod was inserted into the filter pipes, which ran ahead of the filter pipes. The individual filter strings were initially desanded using shock desanding (opening and closing the valve) with the additional use of compressed air in order to build up a thick filter body around the filter strings in the ground. This was followed by intensive desanding. The technical sand-free requirement (residual sand content less than 1 g/m³) specified in ÖNORM B 2601 was verified.

Figure 12. Construction of the horizontal filter well using the *Ranney-Falley* method.

Prior to construction, a borehole was drilled to verify the subsoil conditions at the location of the horizontal filter well. The groundwater table was found at a depth of 8.9 m below ground level. Pump tests with pumping rates of up to 8.8 l/s were carried out in the borehole and revealed a water permeability of the aquifer of $k_f = 1{,}4$ to $6{,}2 \cdot 10^{-3}$ m/s, confirming the planning assumptions.

Due to the relatively low thickness of the aquifer, all filter strings were arranged on one level, with the 10 filter strings located approx. 0.5 m above the groundwater barrier. In addition, six reserve openings were provided in the shaft for possible additional filter stings, with two reserve openings arranged at the level of the filter strings and four reserve openings arranged approximately 0.5 m above the filter strings.

The total usable filter length of the horizontal filter well is 167.2 m (the first 5 m of each string are designed as solid pipes). The originally planned total length of 180 m could not be achieved because barriers were encountered in the subsoil during construction of the individual strings.

4.2 *Seepage trenches and three recharge wells*

The groundwater is returned downstream of the horizontal filter well via near-surface seepage lines in the form of a 150 m long filter line with a DN300 drainage pipe inside a drainage gravel box, whereby the groundwater to be seeped is fed into the filter line at three points for better distribution.

As can be seen in section 4.3, three additional absorption wells were constructed during the construction phase to increase the efficiency of groundwater recharge. The wells have a bore diameter of 900 mm with a casing diameter (filter assembly) of 400 mm and extend to the upper edge of the groundwater barrier.

4.3 *Pumping test and remediation measures*

A pumping test was carried out to proof the capacity of the horizontal filter well, the effects on the aquifer, and to check the conditions nearby to the well. For this test, a network of several groundwater level gauges was set up, both outside and inside the thin diaphragm wall enclosure with its openings. The pumping test was to be carried out in five stages with different pumping rates and observation times: stage 1: 20 l/s; stage 2: 45 l/s; stage 3: maximum possible pumping rate; stage 4: groundwater recharge; stage 5: 150 l/s (max. planned pumping rate).

However, the pumping test revealed several problems in stages 1 and 2 with low pumping rates, so that the following remediation measures were subsequently carried out:

- Repeated desanding of individual filter sections of the horizontal filter well
- Deepening of the shaft base to lower the pumps in the shaft in order to increase the maximum lowering depth (max. lowering to 1.0 m above the filter strings)
- Installation of automatic backwash filters to minimize the effort required to clean the filters from sand
- To improve groundwater communication in the area surrounding the excavation pit, the thin diaphragm wall was additionally to its openings drilled at specific points using large-diameter boreholes (drill diameter 900 mm) and filled with gravel.
- In the area of the seepage trenches, partially thin impermeable soil layers were encountered below the drainage level, causing backwater. To remedy this, the soil was replaced and three additional recharge wells were constructed (see Figure 4).

A next pumping test ultimately was positive, allowing the entire thermal groundwater utilization system to be put into operation.

5 OPERATING PHASE

Since the thermal groundwater utilization system was set into operation in 2013, it has now been in operation for more than 10 years. The following table compares the planning assumptions with the measured values from the 10th year of operation, showing a very good match.

It should also be noted that the authors are not aware of any malfunctions or other impairments.

Table 2. Comparison of planning phase and operating phase.

groundwater data		planning phase 2008 (see section 2.3)	10th year of operation in 2023 (measured)
annual heating work	*MWh*	2500	2412
annual cooling work	*MWh*	5700	5763
max. pumping rate	*l/s*	150	150
mean pumping rate per month	*l/s*	11 – 80	26 – 52
mean annual pumping rate	*l/s*	44	39

6 SUMMARY AND CONCLUSIONS

The discussed project is one of the largest inner-city examples of thermal groundwater utilization in Austria. The aim was to implement an ecologically sustainable energy concept that covers around 65–70% of the campus's heating and cooling requirements through the direct use of groundwater.

The system consists a horizontal filter well for groundwater extraction with a maximum flow rate of 150 l/s. The water is used for heating and cooling purposes and then returned to the groundwater via seepage trenches and recharge wells. The annual heating work is approx. 2500 MWh, and the cooling work is approx. 5700 MWh.

Extensive geotechnical, hydraulic, and thermal modeling was carried out for planning and verification purposes. 2D and 3D simulation models were used to analyze the hydraulic and thermal effects on the groundwater. The impact on existing water rights in the surrounding area was also investigated.

The system has been operating without major difficulty since it was set into operation in 2013. The operating data measured after ten years confirm the originally planned values almost completely.

Overall, the project shows how intelligent planning, model-based analyses, and adapted construction methods can be used to successfully implement a sustainable energy concept for a large inner-city university campus.

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