Lessons Learned from Two Open-Loop Geothermal Systems Using Shallow Aquifers for Heating and Cooling in Geneva, Switzerland

Faÿ Sylvie[1], Bernard Brixel[2], Loïc Quiquerez[1], Nicolas Soureillat[1], Alexandra Bel[3]

[1] Services Industriels de Genève, Geneva, Switzerland

[2] Cantonal Office of the Environment, Geneva, Switzerland

[3] HydroGeoEnvironnement, Geneva, Switzerland

sylvie.fay@sig-ge.ch

Keywords: Open-Loop geothermal systems, shallow aquifers, thermal short-circuit, urban geothermal energy, sustainable heating and cooling, district heating/cooling networks, aquifer thermal recharge, Geneva Canton, GEothermies program.

ABSTRACT

This paper presents a retrospective analysis of two projects undertaken by the Services Industriels de Genève, focusing on the sustainable use of shallow Quaternary aquifers (<60m depth) in Geneva, Switzerland, for geothermal heating and cooling. Given the relatively slow groundwater flow velocities of these aquifers, the development, in collaboration with the State of Geneva through the Geothermies program, of hydrogeological models for long-term temperature variations prediction of these aquifers is essential for ensuring their sustainable exploitation. A central aspect of these projects was the establishment of a comprehensive monitoring system to track temperature variations over time within the aquifers. Through numerical modelling and operational data, the study highlights key challenges such as thermal short-circuit within the aquifer and seasonal imbalance between heating and cooling demands. The paper outlines mitigation strategies including installation of air-coolers or heaters, solar thermal recharge and integration with district heating/cooling networks. These case studies underscore the importance of flexible system design, continuous monitoring, and balanced thermal loads to ensure the long-term sustainability of shallow geothermal resources in urban settings.

1. INTRODUCTION

This paper's general topic concerns the optimization of open loop geothermal systems, also known as groundwater source heat pumps (GWHP), used to heat and cool buildings installed above shallow Quaternary aquifers in Geneva, Switzerland. These systems operate as open loops, i.e. by pumping groundwater from a shallow aquifer via extraction wells, transferring groundwater's thermal energy through a heat exchanger to either a Heat Pump (HP) based system or a thermal distribution network for geocooling purposes, and finally reinjecting water in the aquifer through reinjection wells. Those geothermal systems, based on renewable energy source, can help decarbonize heating/cooling of buildings in urban area where shallow aquifers exist.

In 2020, the Canton of Geneva adopted its own Energy Master Plan (EMP) in order to meet its energy and climate goals and fully commit Geneva to the energy transition. The main target of this master plan is to achieve the "2000-watt/inhab. society" by 2050. This means roughly a 3.5-fold reduction in energy consumption in parallel to tripling the proportion of renewable energies in the current energy-mix of the Geneva canton. As a local and renewable source of thermal energy, shallow and intermediate-depth aquifers present across the region of Geneva are expected to play a major role to achieve the goal of enhancing the proportion of renewable energies.

In 2014, the GEothermies program was jointly launched by the State of Geneva and the Services Industriels de Genève (SIG). This program aims to enhance knowledge of the Geneva subsurface and to establish an institutional framework to help foster the development of this energy resource. The Geneva area is located above large shallow aquifers which are interesting opportunities for developing open loop geothermal systems. Many of these opportunities were identified through the GEothermies program, which led to the design and installation of several open loop geothermal projects. Two of them are presented in this paper. One consists of using geothermal energy for supplying geocooling to a 4-Star hotel. The other project consists of supplying heating and geocooling to new residential buildings equipped with heat pumps (HP). Based on a comparison between simulated and measured data over the first years of operation, this paper focuses on describing flexible approaches to open-loop shallow geothermal system operation.

2. LOCAL CONTEXT

The two geothermal systems presented in this paper (depicted by the two blue circles on the map on Fig. 1) are located over the Montfleury aquifer, one of the four main shallow aquifers present across the Geneva region alongside the Rhône, Genevois and Allondon aquifers. The Montfleury aquifer extends across the north-western part of Geneva, on the shore of the Geneva Lake, with a NE-SW orientation. It consists of layers of variable thickness of sand and gravels that were deposited in fluvio-glacial environments that existed between the Riss and the Würm ice ages. In terms of hydrostratigraphy, these sand and gravels belong to the unit known regionally as the "Alluvion Ancienne", which is sandwiched between the glacial till and more clayey units of the Riss and Würm glaciations. The bedrock, generally found below the Riss unit consists of freshwater Molasse.

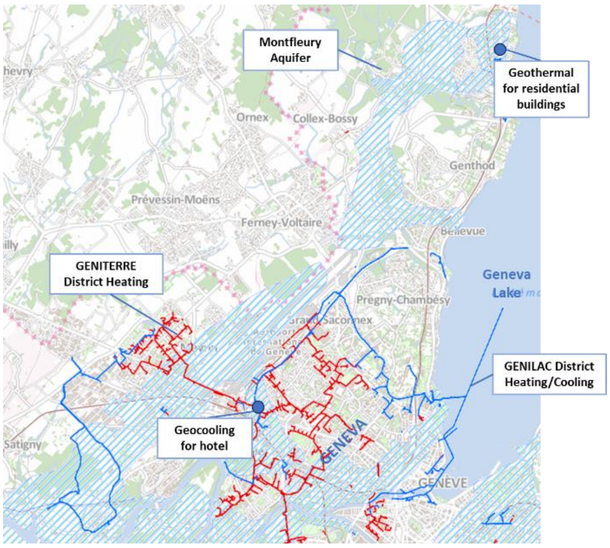

Figure 1: Map of the western part of the Canton of Geneva showing the spatial extent of the Montfleury aquifer, the locations of the two geothermal systems described in this paper and the layout of the GENITERRE and GENILAC district heating/cooling networks.

Extensive hydrogeological field work and numerical modelling showed that the spatial extent of the Montfleury aquifer is relatively large but that its structure and geometry are complex. It is also characterized by low hydraulic gradients (~ 0.1%). This is an important point for open-loop geothermal systems. It implies that distances between extraction and reinjection wells smaller than 200–300 meters can lead to thermal short-circuiting, resulting potentially in poor performance or even unsustainable systems.

With cross-well distances ranging from 100 to 160 meters, the two systems presented in this paper needed to plan for, and in one case rapidly install, mitigation measures to counteract the thermal short-circuits observed or expected in the medium term.

Fig. 1 also shows the layout of the two main district heating/cooling networks of the Geneva Canton, referred to as GENITERRE (high-temperature network) and GENILAC (low-temperature network). The GENITERRE district heating network (shown in red) is a warm water network (110°C–65°C) supplied by a gas plant and a waste incineration plant. Other renewable heat sources will be integrated in GENITERRE in the future, such as intermediate-depth geothermal energy, in order to gradually increase the share of renewables in this network, in order to reach the target of 80% renewable energy by 2030.The GENILAC network (shown in blue) is a cold-water network that uses lake water as its renewable source. This district network is primarily used to provide cooling during the summer. In winter, decentralized heat pumps (HPs) installed in buildings connected to GENILAC provide heating. Studies on the expansion of the GENILAC network have shown that as winter heating demand increases with the network's growth, the average temperature of the network will gradually drop during winter, reducing the coefficient of performance (COP) of the connected HPs. Since the Montfleury aquifer lies beneath part of the GENILAC route, discussions are ongoing about using this shallow groundwater as an additional source during winter to complement the lake, whose intake temperature is lower than groundwater temperatures.

3. GEOCOOLING FOR A 4-STAR HOTEL

3.1 Geothermal installation

This geocooling-based geothermal system operates since May 2022 and provides cooling for a 4-star hotel. For heating, a connection to the GENITERRE network—running alongside the project parcel—was chosen instead of installing a heat pump on the aquifer, as the hotel's heating demand exceeds its cooling demand.

The cooling system provides 520 kW at heat exchanger with a nominal flow rate of 150 m³/h and a ΔT of 3°C (water is pumped at 13°C and returned at 16°C). The installation (schematic drawing shown on Fig. 2) consists of two extraction and two reinjection wells with a diameter of 800 mm and spaced approximately 100m apart. The natural water table is found around 30m below ground surface, showing little variation across seasons and stable groundwater temperature around 13°C.

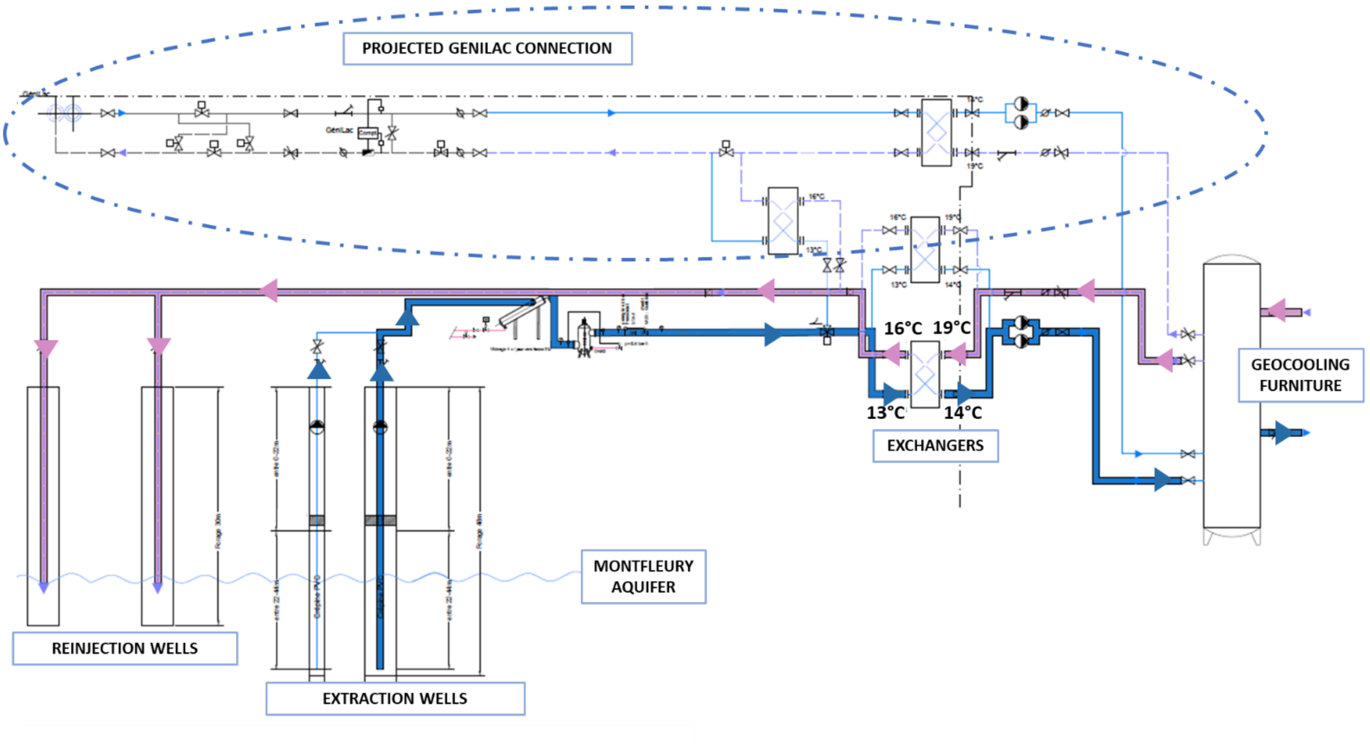

Figure 2: schematic drawing of the open-loop geothermal system that supplies geocooling to a 4-Star hotel in Geneva, Switzerland. The temperature of the geocooling hotel loop is cooled down to 14°C by 520 kW heat exchangers connected with two extraction wells and two reinjection wells drilled on the Monfleury aquifer. Connection to GENILAC district network is planned within the next few years, in order to supplement the hotel's cooling during the summer and to use the Montfleury aquifer during the winter to prevent the average temperature of GENILAC from dropping too low.

3.2 Projected groundwater temperatures and thermal conditions on site

To evaluate the impact of the geothermal system on the Montfleury aquifer on and in the direct vicinity of the site, initial simulations based on a numerical groundwater flow and heat transport model were performed. The projected temperatures at the extraction and reinjection wells are shown in Fig.3.

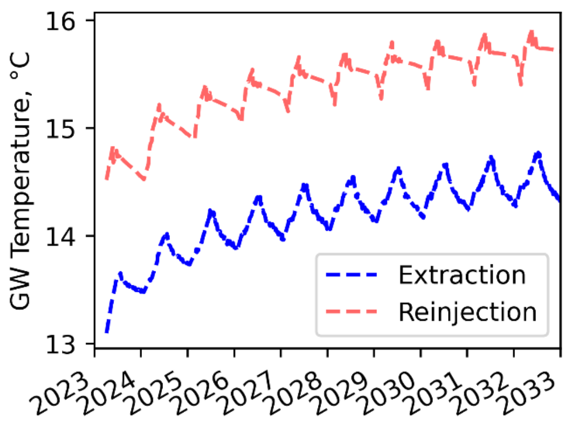

Figure 3: Projected gradual increase in groundwater temperatures at the extraction (blue) and reinjection (red) wells based on numerical flow and heat transport simulations performed as part of the initial feasibility study for the development of an open-loop shallow geothermal system for a 4-star hotel in Geneva located above the Montfleury aquifer (see Fig. 1).

These simulations revealed that a thermal drift would rapidly occur in the hydrogeological system, due to the low piezometric gradient of the aquifer and relatively close proximity of the extraction and injection wells, but also by the fact that only the hotel's cooling needs are covered via the aquifer (not the heating needs). This means that the temperature increase of the extracted water used for geocooling during the summer season could not be compensated during the winter season by a cool-down temperature of the extracted water used for heating (via HP).

In detail, simulation results showed:

- Rapid thermal drift during the first five years.
- After five years, the extraction well temperature would rise from 13°C to 15°C, and the reinjection well from 13°C to 18°C.
- After ten years, the extraction well would reach 16°C, and the reinjection well 19°C.

During the project planning phase, this risk of thermal short-circuit was mitigated by considering the arrival of the GENILAC district heating network within two years of operation—i.e., before thermal short-circuiting would significantly impact cooling delivery. Once connected, GENILAC would supplement the hotel's cooling in summer (as described in Fig. 2), avoiding thermal short-circuiting, and in winter, the aquifer would recharge GENILAC, replacing lake water as source.

3.3 System monitoring and mitigation measures

Unfortunately, the thermal short-circuit that occurred within the first year of operation significantly impacted the system's cooling capacity far more than what had been anticipated by the simulations. Additionally, the hotel's secondary circuit was not optimally designed for cooling regulation, leading to excessive cooling even in winter when aquifer naturally-recharge was originally planned. As a result, Fig.4 shows that the aquifer temperature at the start of the second summer season was already 14°C—nearing the critical limit for comfortable cooling.

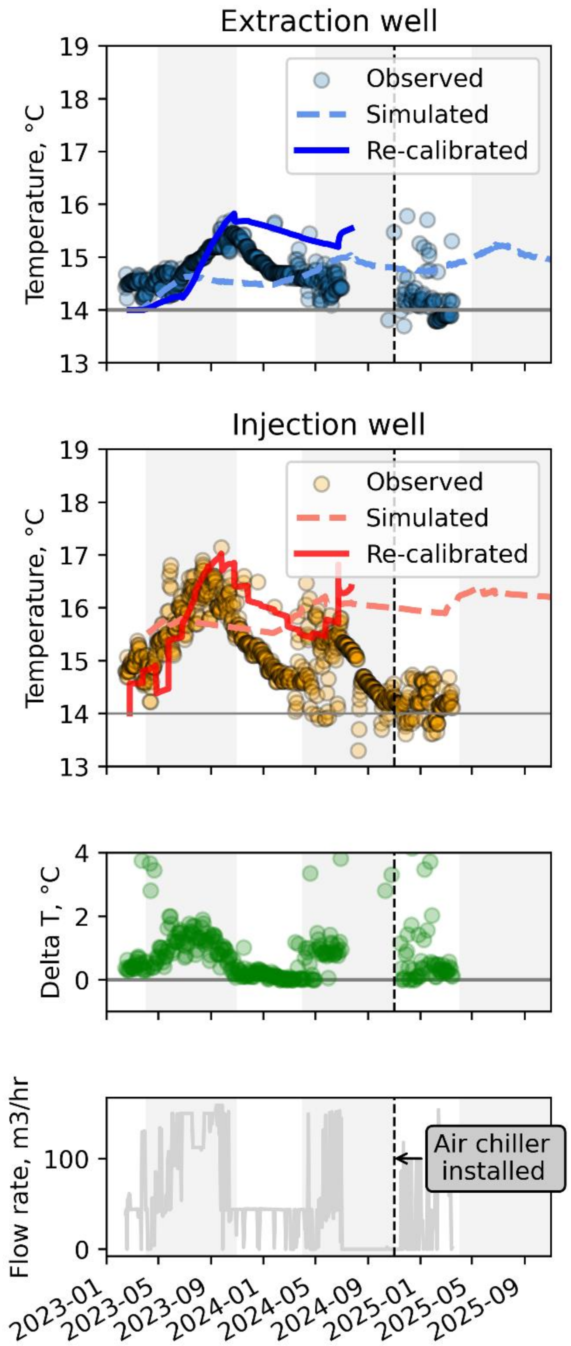

Figure 4: Monitoring dataset comparing time trends between observed groundwater temperatures at the extraction and injection wells (top panels) as well as the temperature differential between the extracted and reinjected water and the operating flow rate (lower panels). The original simulated temperatures projected at the design stage are shown as solid lines, while the projection based on a recent re-calibration of the numerical model are shown as dashed lines. The vertical dashed line shows the time when the air chiller began to operate.

Cooling delivery to a hotel requires a continuous temperature that does not exceed 14°C. Given that the Montfleury aquifer's base temperature is 13°C, the margin for temperature estimation errors is narrow. Even small variations in expected temperature trends over the year can lead to significant deviations in the temperatures delivered to the hotel's exchangers.

To ensure reliable cooling, the secondary geocooling circuit was first optimized to maximize winter aquifer recharge. Knowing, however, that this would not be enough to maintain a temperature below 14°C, a mechanical chiller with an air-cooled condenser was installed in autumn 2024, as shown schematically on Fig.5. It activates when aquifer temperature exceeds 14°C, in order to pre-cool extracted water before injecting it into the hotel's geocooling system at 13°C. Also, during cold winters, the air-coolers of this system can be activated to overcool the aquifer, thereby boosting its summer cooling potential.

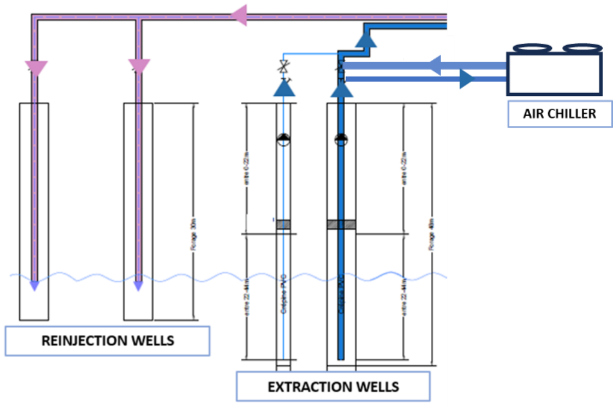

Figure 5: Schematic drawing of the adding of an air chiller to the open-loop geothermal system. By activating as soon as the aquifer temperature exceeds 14°C, this air-chiller allows to pre-cool the extracted water before injecting it into the hotel's geocooling system.

At the time of writing this paper, the installed air-chiller has not been activated so far. Indeed, during summer 2024 this system was not ready to be installed. As the temperature of the aquifer started to reach again critical values, the geothermal open-loop system was disconnected and urgently replaced by a backup air conditioning system. This emergency measure had the advantage of allowing the aquifer temperature to gently decrease during the remainder of the summer 2024, as illustrated by the first two graphs in Fig.4. Further monitoring during summer 2025 will therefore be required to evaluate the impact of the "air chiller" mitigation measure on the thermal state of the aquifer and its capacity to meet the hotel's cooling requirements.

4. HEATING AND GEOCOOLING SOURCE FOR NEW RESIDENTIAL BUILDINGS

4.1 Geothermal installation

In contrast to the previous system, this open-loop geothermal system is located in a part of the Canton that will not be connected to any major heating or cooling networks. Hence, there is no possibility to rely on such solution to mitigate any risk of thermal short-circuit over time. The system uses aquifer as a cold source for new residential buildings equipped with heat pumps (HP) for heating, and radiant floors for cooling. Geocooling via radiant floors ensures partial aquifer recharge during the warm season.

The geothermal doublet consists of one extraction and one reinjection well, each 250 mm in diameter. The system has a maximum flow rate of 90 m³/h, corresponding to a power supply at heat exchanger of about 480 kW (ΔT ~ 4–5 K). It is designed to supply three substations (SST) with about 160 kW of power supply each, as illustrated in Fig.6. The wells are spaced ~150 m apart.

The water table is found around 10 m below ground surface, shows only minor (< 1 m) fluctuations across seasons and a stable groundwater temperature around 13 °C.

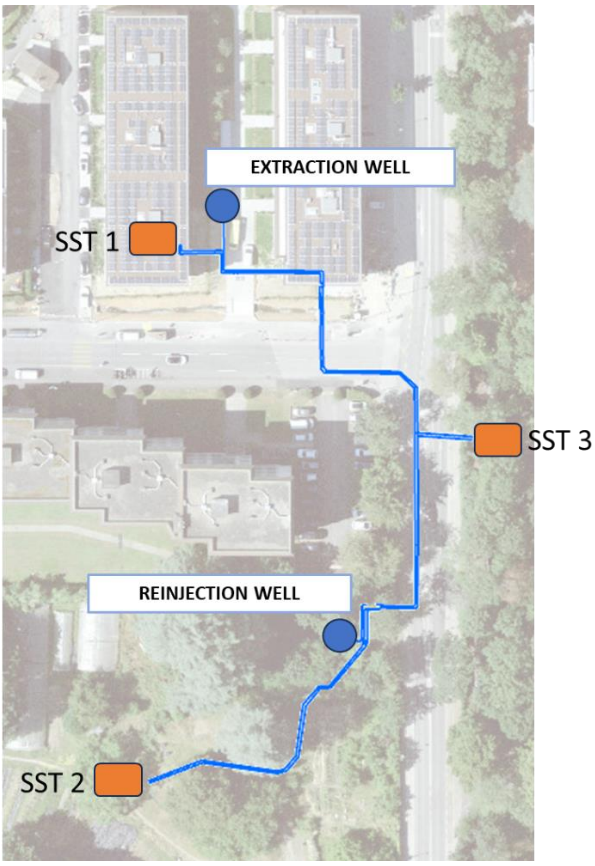

Figure 6: Geographical layout of the open-loop geothermal system used as a cold source for three substations (SST) of new residential buildings equipped with heat pumps (HP) for heating, and radiant floors for cooling.

Only one substation (SST1) was built at the end of 2023. The buildings to be connected to SST2 are under construction, and SST2 is scheduled for commissioning by the end of 2026. Buildings for SST3 are still in the planning phase.

4.2 Modelling and hydrogeological simulations before commissioning

A numerical groundwater flow and heat transport model was built and calibrated against field data collected during a comprehensive exploration campaign performed during 2017-2020. The first hydrogeological simulations were performed based on SST1's heat and cooling consumption, which were estimated around 500 MWh/year for heating, leading to an extracted energy from aquifer of ~ 345 MWh/year (assuming a COP of 3 for the heat pump), and 70 MWh/year for cooling. The year repartition of the demand is shown on the Fig.7, including both projected and measured energy consumption (for year 2024).

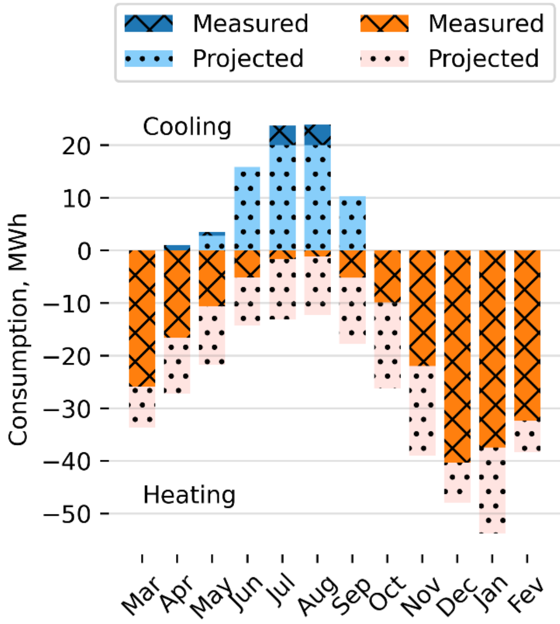

Figure 7: Comparison between projected and measured heat and cooling demand for the first year of operation (2024) of an open-loop shallow geothermal system for two new residential buildings (SST1) recently constructed in the northern part of Canton Geneva, on one of the main hydrogeological compartments of the Montfleury aquifer, close to the lake (see Fig. 1).

Results of the flow and heat transport simulations, illustrated on Fig.8, showed that we should expect the onset of thermal drift, again due to a low hydraulic gradient of the aquifer, but also the unbalanced ratio of heat and cooling demand (83% of heating demand vs 17% of cooling demand). After 20 years of operation, with one substation only, the simulated aquifer temperature at reinjection well would vary between 1°C and 5°C, and still not stabilize.

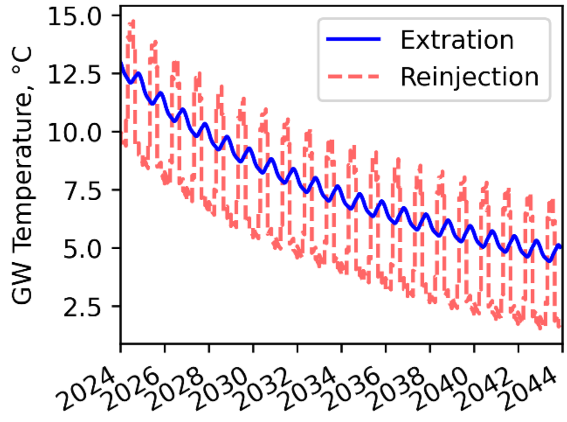

Figure 8: Projected gradual decline in groundwater temperatures at the extraction (blue) and reinjection (red) wells based on numerical flow and heat transport simulations performed as part of the initial feasibility study for the development of an open-loop shallow geothermal system for two new residential buildings (SST1) in Geneva Canton (see Fig. 1).

4.3 System monitoring and mitigation measures

Monitoring of groundwater temperatures at the extraction and reinjection wells has been performed during the first year of operation with only the SST1 in charge. The observed data are plotted in the Fig.9, along with the simulated data.

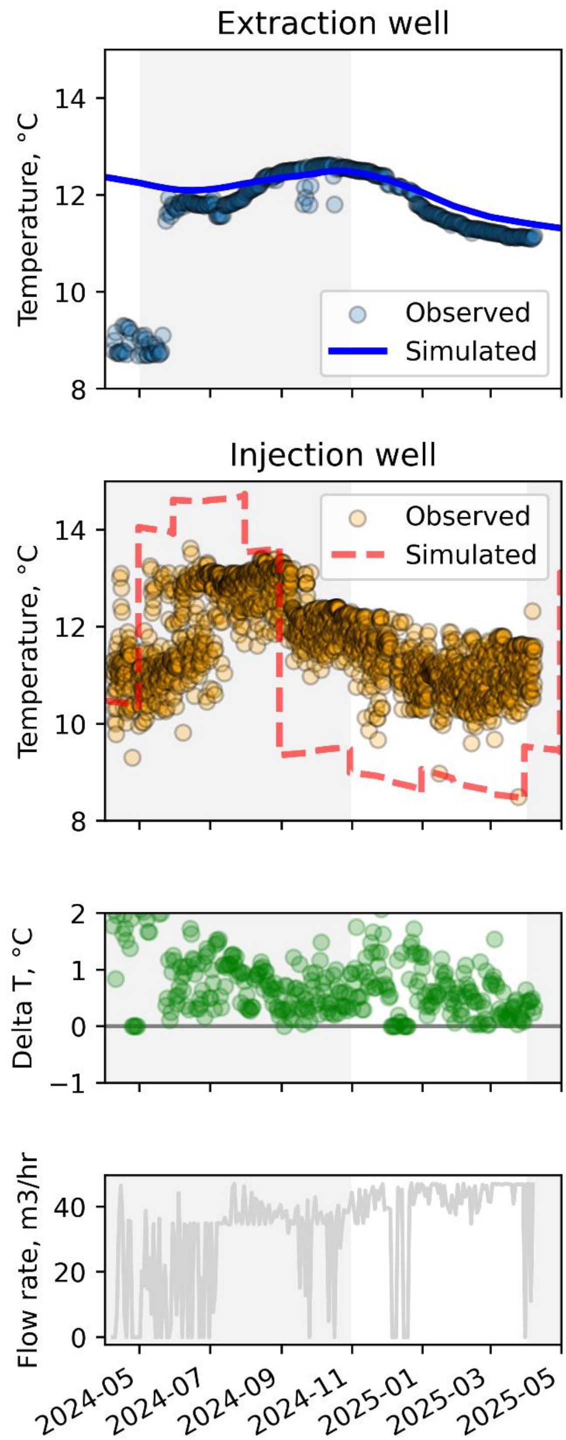

Figure 9: Monitoring dataset comparing time trends between observed groundwater temperatures at the extraction and injection wells (top panels) as well as the temperature differential between the extracted and reinjected water and the operating flow rate (lower panels).

The plot of the measured temperature at extraction well during the first year of operation show that a seasonal thermal drift is observed, following the general trend of the simulated curve. On the other hand, the strong deviation between observed and simulated temperature at the reinjection well, especially during the winter season, seems surprising. It can however be explained if we consider the lower ΔT values (below 2°C) observed at the heat exchanger installed at SST1. That would mean that a much lower heating power was supplied to SST1 during the winter season. Indeed, the measured consumption of SST1, plotted on Fig.7, indicates that during the year 2024, the heat demand has been 60% less than the one estimated, whereas the cooling demand was well fitted with the one estimated. This reduced heating demand has induced a slightly better-balanced heating/cooling ratio (74%/26%), which could explain the lower thermal drift observed. Still, the temperature at extraction well is lower after one year of operation compared to its initial (pre-pumping) state. This suggests that the instability of the temperature after 20 years of operation shown with the simulated data will probably be confirmed, especially since two more substations are planned to be added to the geothermal installation.

Based on these observations, several mitigation measures have been or will be implemented in the three substations of the geothermal system:

- Bypass right after the SST1's heat exchanger to remove part of the cooled groundwater intended to be reinjected in the aquifer by rejecting it to the clear water system: this mitigation measure has been installed preventively during the construction of the geothermal installation. It has not been activated so far, as the thermal drift observed after the first year of exploitation remained negligible. But it will probably be activated during the next years of operation, when the two other substations will be built. Nevertheless, this type of mitigation strategy, which entails the permanent withdrawal of a portion of the groundwater abstracted from the hydrogeological system, should not be implemented at a broad scale, as it may progressively induce hydraulic perturbations and disequilibria within the aquifer over the medium to long term.

- Implementing additional summer aquifer recharge via thermal solar collector or air-heaters on the next substations: new buildings that are under construction and planned to be connected to the future SST2 of the geothermal installation are also residentials buildings using HP for heating and radiant floors for geocooling. As for the buildings connected to SST1, it is likely that the unbalanced ratio of heat and cooling demand will reinforce the long-term thermal drift of the aquifer. In this case, instead of installing another ground water bypass towards the clear water system, some space on the roofs of the new buildings as been reserved to install thermal solar collectors that will be used specifically to recharge the aquifer during the summer season (see Fig.10). The surface area of the thermal solar collectors has been designed to ensure that seasonal recharging during the summer period restores the aquifer temperature to a value equal to or greater than that measured at the onset of the heating season.

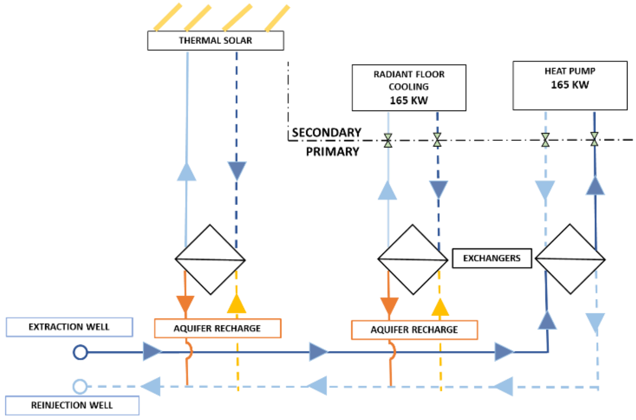

Figure 10: Schematic drawing of the adding of thermal solar collectors at the next substation (SST2) that will be connected to the open-loop geothermal system. Those solar collectors will strengthen the recharge of the aquifer during the summer season in order to counteract the thermal drift that would develop over time due to unbalanced heating/cooling demand of the new residential buildings connected to the GWHP system.

Since SST2 is not expected to be commissioned before the end of 2026, the effect of the solar thermal collectors as a mitigation measure to ensure sustainable interseasonal recharge of the aquifer cannot be validated before that date. Meanwhile and thereafter, the aquifer will continue to be monitored, and the measured data will be compared with the simulated data and cross-referenced with heating/cooling consumption of the residentials buildings supplied by the GWHP system.

6. CONCLUSIONS

Through feedback from these two open-loop groundwater geothermal projects, the importance of properly aligning the resource with surface-level consumer demands has been emphasized.

On one hand, there is a complex resource that is only partially characterized, and which we try to better characterize through exploration campaigns and model construction—models that, as observed, remain simplified versions of a complex reality.

On the other hand, the projects' heating and cooling demands are rarely balanced, which requires the addition of mitigation measures such as thermal solar collectors or air coolers/heaters recharge systems. In some cases, these measures can drastically worsen project costs.

Interactions of these groundwater source heat pumps (GWHP) systems with the two main district heating networks of the Geneva Canton (GENITERRE and GENILAC) have also been briefly addressed. Indeed, these networks could, in some cases, be used to supplement the heating or cooling supply to buildings connected to GWHP installations, in order to stabilize the aquifer's interseasonal charging/discharging cycle over the long term.

Finally, the experience gained from these two open-loop groundwater geothermal projects has shown that:

- Continuous monitoring of the installations is essential, not only to evaluate performance, but also to anticipate potential thermal interference as early as possible and to implement mitigation measures that ensure the sustainability of the geothermal resource.
- The design of hydrogeological models to simulate the long-term behavior of the aquifer subjected to seasonal charge and discharge cycles is also very important. By being refined with new data from the monitoring of shallow aquifer geothermal systems, these models make it possible to plan the development of new groundwater geothermal systems while ensuring both optimal resource sharing and long-term sustainability.
- In view of all the uncertainties regarding the resource and surface energy needs, it is also very important to design groundwater geothermal systems to be as flexible as possible from the outset.