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Nested Shallow Geothermal Systems

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Abstract: The long-term sustainability of shallow geothermal systems in dense urbanized areas can be potentially compromised by the existence of thermal interfaces. Thermal interferences between systems have to be avoided to prevent the loss of system performance. Nevertheless, in this work we provide evidence of a positive feedback from thermal interferences in certain controlled situations. Two real groundwater heat pump systems were investigated using real exploitation data sets to estimate the thermal energy demand bias and, by extrapolation, to assess the nature of thermal interferences between the systems. To do that, thermal interferences were modelled by means of a calibrated and validated 3D city-scale numerical model reproducing groundwater flow and heat transport. Results obtained showed a 39% (522 MWh$\cdot$yr^{-1}) energy imbalance towards cooling for one of the systems, which generated a hot thermal plume towards the downgradient and second system investigated. The nested system in the hot thermal plume only used groundwater for heating, thus establishing a positive symbiotic relationship between them. Considering the energy balance of both systems together, a reduced 9% imbalance was found, hence ensuring the long-term sustainability and renewability of the shallow geothermal resource exploited. The nested geothermal systems described illustrate the possibilities of a new management strategy in shallow geothermal energy governance.

Keywords: geothermal energy; low enthalpy; groundwater; heat pump; nested systems

1. Introduction

Anthropogenic climate change is a major public concern worldwide [1]. An economy with net-zero greenhouse gas emissions is the objective of the European Green Deal in line with the EU's commitment to global climate action under the Paris Agreement. Taking into account that the heating and cooling sectors account for more than 47% of the final energy consumption in Europe [2], and that 81% of this energy is consumed by burning fossil fuels, it is a fact that further transition to renewable energy in this sector is required. In this framework, shallow geothermal energy (SGE) as a well-developed, efficient, and clean technology [3] has the potential to become a cornerstone in the reduction of greenhouse gas emissions, the increase of renewables in energy consumption, and the increase of energy efficiency, all foreseen EU Energy targets for 2030 [4].

An estimation of the installed thermal power and thermal energy use for shallow geothermal energy at the end of 2019 was 77,547 MWt and 599,981 TJ$\cdot$yr^{-1}, respectively [5]. The steady increase of installations evidences the success of this emergent technology but, at the same time, poses some potential sustainability issues related to massive development of systems in urban areas. Such sustainability problems are related to, among others, thermal interferences between systems [6]. Thermal interference is a well-studied phenomena in shallow geothermal systems [7]. Potential interference between closed geothermal systems [8] in high-density populated urban areas has been described using different mathematical models, both numerical [9] and analytical [10]. Monitoring of subsurface temperature changes in areas of high density in SGE systems is necessary to establish the space requirements between individual systems, thus defining viable densities of these systems. However, the establishment of the minimum distances between systems is still under discussion. The proposal [11] of a method to evaluate the size of the area of influence of a determined borehole heat exchanger (BHE) considered the absolute distance between a central BHE surrounded by two consecutive BHE rings. The study of thermal interferences between closed systems has questioned the long-term sustainability of the exploitation of SGE energy in urban areas with high system density. This is due to the fact that it takes a long period of time to reach the steady state of the exploitation regimes. In fact, it takes several decades to guarantee that the thermal impacts are stable over time and the exploitation is sustainable in the long term. BHEs in areas of high system density should be 2, 3, or 6 times deeper than those for fully isolated systems for system lifetimes of 15, 25, and 50 years [12], respectively, given an operation with the same thermal loads and exploitation regimes throughout the year. The trend to drill deeper BHEs (>200 m) to avoid problems was already observed in Sweden [13]. Furthermore, the inverse relationship of depth and distance between BHEs was investigated [14]. The interference between BHEs was evaluated numerically in terms of the heat transfer rate per drilled meter to estimate the associated loss of efficiency [15]. The results obtained indicated that a distance of 4.5 m between BHEs is sufficient to limit total performance losses to values below 10% with a continuous operating rate of 2400 h and a high thermal conductivity value of 4 $W{\cdot}m^{-1}{\cdot}K^{-1}$, which would be the most unfavorable scenario. Surprisingly, and opposed to the latter, it was demonstrated [16] that a distance of 6 m between BHEs, as recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [17], may be insufficient to avoid thermal interferences, especially when the systems present strong imbalances in the heating–cooling thermal loads throughout the year. However, none of these studies took into account heat advection by groundwater flow, even though the spacing between BHEs is an important factor [18]. To prevent or even eliminate thermal interferences, other authors have proposed the interconnection of facilities using ultra-low temperature district heating and cooling networks (DHCs) [19].

On the other hand, thermal interference between open systems (groundwater heat pump systems or GWHPs) occurs when the production well(s) pumps groundwater affected by the injection well(s) of other SGE systems in the surroundings. If a thermal interference is produced, the efficiency of the SGE system will be compromised and, in extreme cases, the economic viability can be lost. Furthermore, performance decline induces a positive increase of the electrical energy required to operate the heat pump. Such an increase will inevitably result in an increase of greenhouse gas emissions, especially when the electrical energy consumed comes from a fossil fuels-based mix. Evidence of thermal interference was documented in the Po-Venice Plains region (Italy) related to a low hydraulic gradient and a lack of available space in densely populated historic urban areas [6] and urban areas presenting a high density of SGE systems (open systems) and high hydraulic transmissivity, such as Basel (Switzerland) [20] or Zaragoza (Spain) [21], among others. When thermal interferences occur within an open system, two types of thermal interference are distinguished [22]: (1) thermal feedback when the injection temperature is fixed and the collection temperature varies but does not condition the discharge temperature [23]; and (2) thermal recycling when the thermal change between the pumped and the injected temperature is superimposed, thus conditioning the injection temperature to the extracted temperature. To mathematically describe the phenomenon of thermal recycling, an algorithm based on a semi-analytical solution or a numerical approximation is required [24].

The thermal feedback phenomenon was studied using particle tracking in open systems with several injection-capture wells exhibiting complex configurations [25].

The "Sustainable development and exploitation of SGE resources" was recognized as one of the fundamental policy principles in the governance of shallow geothermal energy resources [26]. This policy was introduced in order to prevent different management problems, including the negative thermal interferences. Thermal interference is an important management concept considered as a first order management problem in license procedure, not only in academia [27] but also in legal frameworks worldwide [28]. Furthermore, to prevent thermal interferences between SGE systems, thermally affected zones (TAZs) [29] and thermal protection perimeters (TPPs) [30] around geothermal installations were defined.

Although intensive use of shallow geothermal resources leads to dense installation areas where thermal interference can potentially decrease efficiency, in this work we postulate that controlled thermal interferences can induce symbiotic (positive) relationships between systems, thus increasing the performance of the systems involved. In this work, current observations made on the exploitation patterns of groundwater heat pump systems in the city of Zaragoza (Spain) [31] were revised to reveal the existence of positive thermal interferences between two GWHP systems. It was observed that one of the GWHP systems (nested system) was located within a hot plume or TAZ generated from an upgradient GWHP system (host system). Systems within thermal plumes of other systems that take advantage of such situations are here referenced as nested shallow geothermal systems. The objective of this work is to describe an existing identified nested system in the urban aquifer of Zaragoza city (Spain) as a representative case of symbiotic (positive) thermal interference, which has not been documented in the literature before. Then, the implications of symbiotic relationships between systems of SGE resources management are discussed.

The contribution of this paper in defining novel management strategies of shallow geothermal thermal impacts poses an advancement in the environmental performance of geothermal technology in comparison to other renewable energy systems [32], thus providing long-term sustainable designs of geothermal systems [33]. Furthermore, the nested geothermal systems concept conforms new possibilities in future sustainable development in urban areas [34].

2. Methodology

2.1. Study Area

The identified symbiotic relationship between SGE systems can be found in the city of Zaragoza, in the northeast of Spain (Figure 1A). The systems make use of a shallow urban aquifer constituted by quaternary alluvial deposits formed by siliceous and carbonate grain-supported gravels in high lateral extension forming tabular bodies with cross-bedding with intercalated sandy lenticular bodies [35]. The water table under the city can be found at 5 to 40 m depth and the saturated thickness of the aquifer ranges between 5 and 40 m. Alluvial deposits of the aquifer overlay a sub-horizontal gypsum and marl layers package conforming the aquifer basement [36]. The shallow urban aquifer of Zaragoza city is one of the most investigated urban aquifers sustaining an intense shallow geothermal energy exploitation [37–39]. Within the groundwater body, a total of 47 specifically constructed piezometers conform a geothermal monitoring network used by the Spanish Geological Survey (IGME) to control the thermal use of groundwater for the last 12 years [40]. There are more than 73 GWHP systems catalogued in the city of Zaragoza, involving more than 188 water wells, 112 for captation and 76 for injection (Figure 1B). The total installed power of all the GWHP installations in Zaragoza city is approximately 110 MW [41]. Current groundwater extractions in the city of Zaragoza are in the order of 24 $Mm^3 \cdot yr^{-1}$ and are used for watering public parks and gardens (14%), processing of water supplies (8%), recreational use (10%) and geothermal use (68%) [40]. Although 24 Mm^3 of groundwater is pumped every year for heat exchange purposes, only 7.4 Mm^3 is consumed due to groundwater reinjection to the urban aquifer after being extracted.

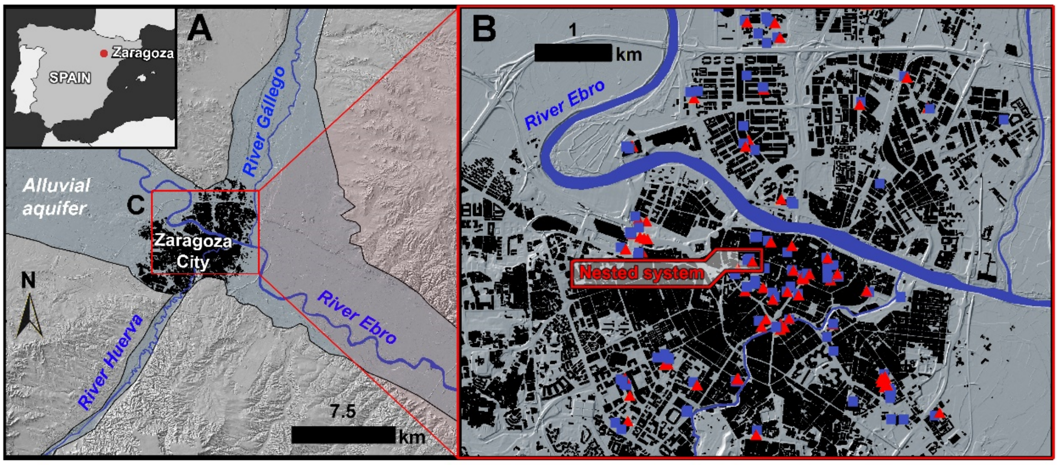

Figure 1. Location of the nested shallow geothermal system investigated in the northeast of Spain. (**A**) Alluvial aquifer extension relative to (**B**) the city of Zaragoza. Captation and injection wells of the existent shallow geothermal systems in the city of Zaragoza are represented by blue squares and red triangles, respectively.

2.2. Host-Nested System and Data Acquisition

Positive thermal interferences establishing a symbiotic relationship were identified between a Regional Government Building (host system) and a Municipal Sports Complex (nested system) in the shallow urban aquifer of the city of Zaragoza (Figure 1B). The host system, labeled here as SGS-H, is a GWHP system operating since 1985. With an installed capacity of 1746 kW, it provides heating and cooling to a 28,000 m^2 indoor space. The system makes use of three geothermal heat pumps connected to three captation and one injection wells of 40 to 47 m depth. On the other hand, the nested system, labeled here as SGS-N, is also a GWHP system installed in 2002. This system presents a 406 kW installed capacity, providing heating (not cooling) to 495-m^3 indoor swimming pools. The system makes use of two captation and one injection wells of 30 to 33 m depth. These systems are separated 167 m from each other. The space disposition of the geothermal wells will be shown later on.

The Geological Survey of Spain (IGME) has been acquiring GWHP operation data sets from 27 systems in Zaragoza since 2014, based on a collaboration agreement with the regional water authority. To date, more than 1.82 million measurements of pumping/injection flow rates and captation/injection temperatures with a 15-minute cadence have been collected. Captation/injection water temperatures were measured using immersion temperature sensors installed in the pipeline of the respective wells and the data logged were stored in a centralized control system. Sensors used were Pt1000- and Ni1000-passive thermo sensors with a measurement accuracy of ±0.2 K and ±0.4 K, respectively. Operation flow rates were measured using commercial electromagnetic flowmeters with a measuring accuracy of ±0.5%. Flowmeters were equipped with a transmitter connected to a centralized control system that registered data measurements of the installations monitored. The 15-minute cadence data set utilized for this work covered a one-year operation period between February 2016 and March 2017.

Thermal energy utilized by SGE systems was assessed considering the energy transported by advection as $P = Qc_w\rho_w\Delta T$, where P [W] is the heat flow transferred, c_w [$J{\cdot}kg^{-1}{\cdot}K^{-1}$] is the heat capacity of water, ρ_w [$kg{\cdot}m^{-3}$] is the water density, and ΔT [K] is the temperature change between the pumped and the injected groundwater temperatures. The upscaling procedure described in [42] was followed, using a monthly thermal integration period to perform a monthly energy balance analysis of the systems.

2.3. Groundwater and Heat Transport Numerical Model

Positive thermal interference analysis was performed using the finite element code FEFLOW [43], which allowed reproducing the conductive and advective heat transport by groundwater in the urban area subsurface. A three-dimensional (3D) model was constructed with an extension of 14,054 m × 14,307 m × 205 m (Figure 2A) and dimensioned to provide a city-scale simulation without border effects. The domain was discretized using a 3D unstructured finite element mesh of 913,983 elements and 484,264 nodes distributed in 21 layers (Figure 2B,C). The total simulated period was three years, which is the time required to reach the steady state in heat transport between the investigated systems.

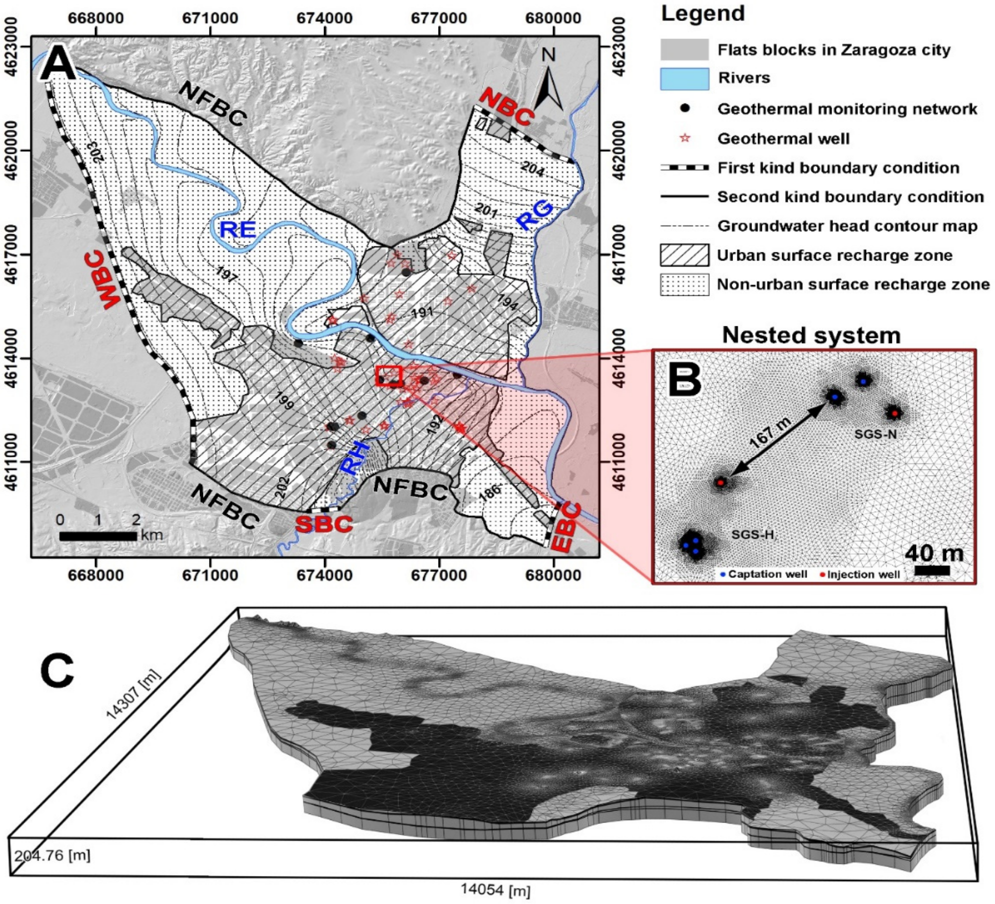

Figure 2. (**A**) Flow and heat transport model domain and boundary conditions used. Hydraulic heads (m.a.s.l.) calculated for January 2016. Geothermal monitoring network and geothermal wells used by GWHP systems in the city of Zaragoza are shown. (**B**) Finite element mesh refinement around SGE systems investigated. (**C**) Finite element mesh used for the city-scale flow and heat transport model.

Groundwater flow boundary conditions adopted in the hydrogeological model are shown in Figure 2A. A transient third boundary condition was imposed on the rivers converging in the city of Zaragoza: River Ebro (RE), River Huerva (RH), and River Gállego (RG). The leakage coefficients were estimated to reproduce the head measurements and hydraulic connection between surface water and groundwater calculated in previous modelling in the investigated area [44]. The river heads were assigned using global coverage topographical information and were modified over time according to the modulation of the time function to reproduce flood events and lateral groundwater recharge. The western (WBC), eastern (EBC), southern (SBC), and northern (NBC) boundary conditions were prescribed as first kind boundary conditions, corresponding to the head contours of previous hydrogeological maps [45] and representing the hydraulic lateral continuity with the rest of the regional alluvial aquifer. Finally, a no-flux boundary condition (NBC) or second kind boundary condition with zero flux was assigned to reproduce aquifer contact with the aquifer bedrock. Surface recharge condition (Neumann condition) was assumed to be stationary with two differentiated zones. In the first recharge zone, a 500-mm flux was imposed in urban recharge zones and, in the second zone, a 20-mm flux was imposed in non-urban areas, according to previous regional models [45]. A total of

72 GWHP systems were implemented in the model by assigning flow rate time functions to nodes representing geothermal wells when data sets were available. For the remaining systems, only annual extraction–reinjection rates were considered.

Regarding the heat transport problem boundary conditions imposed on the model, an upward heat flux of 0.07 W·m^{-2}, according to the continental average geothermal heat flux, was assumed at the base domain boundary. A first kind boundary condition of 17 °C was imposed as the background temperature of the aquifer [46] on all first and second kind domain boundary conditions in the groundwater flow problem outlined above, including recharge boundary conditions. In addition, a transient prescribed temperature boundary condition was imposed on river–aquifer boundary conditions (third boundary condition in the groundwater flow problem). Imposed temperature functions corresponded to surface water temperatures measured by gauging stations within the study area. In line with observations and calculations made by [20], seasonal air temperature fluctuations were assumed to rapidly become dampened before reaching the water table, therefore considering a no-heat flux in the top boundary condition of the model (air–ground interphase). GWHP systems were implemented in the model as transient first kind boundary conditions. Detailed temperature injection regimes were used from the systems monitoring data sets available. For the rest of the systems, cyclical trends observed in the measured GWHP systems were extrapolated, taking into account their respective energy balances.

The model departed from the steady-state modeled piezometric surface from 2004 [45] and an initial constant temperature distribution of 17 °C, which was the background temperature of the aquifer. Parameterization of the model is provided in Table 1, showing the previous calibrated flow and heat transport parameters [47] based on the inverse problem posed in the framework of the maximum likelihood theory [48] and taking into account the lithology of the aquifer and its range of variation [49].

Table 1. Hydraulic and heat transport parameters used in the numerical model.

Parameters	Values	Units
Transmissivity	60–3000	m^2·d^{-1}
Storativity	1E–3–0.3	–
Thickness of aquifer	1–60	m
Porosity	5–30	[%]
Liquid volumetric heat capacity	4.2	MJ·m^{-3}·K^{-1}
Solid volumetric heat capacity	2–2.52	MJ·m^{-3}·K^{-1}
Fluid thermal conductivity	0.65	W·K^{-1}·m^{-1}
Solid thermal conductivity	0.52–2.9	W·K^{-1}·m^{-1}
Longitudinal thermal dispersivity	0.1–5	m
transverse thermal dispersivity	0.1–1.95	m

3. Results and Discussion

3.1. Thermal Energy Balance of the Host-Nested System

Results obtained from the monthly thermal energy balance analysis performed on the host and nested GWHP systems are shown in Figure 3. The host system (Figure 3A) presented a biased energy balance towards cooling. While heating operations absorbed a total of 337 MWh·yr^{-1} from the aquifer during the months between November and April, the cooling operations dissipated 860 MWh·yr^{-1} of heat to the aquifer from June to October. The imbalance of the host system was 522 MWh·yr^{-1} towards cooling. The imbalance represented 39% of the total energy transferred throughout the year. On the other hand, the nested system (Figure 3B) located downgradient presented a monthly energy balance where only heating was produced, absorbing 709 MWh·yr^{-1} of heat from the alluvial aquifer throughout the year, except in July and August. This 100% imbalance of the nested system exceeded the imbalance of the host system by only 186 MWh·yr^{-1}. This means that the simultaneous operation of both systems resulted, with respect to the aquifer, in a 9% imbalance towards heating. The result of this 9% imbalance towards heating was a downgradient cold plume, which is desirable in an already heated aquifer that is intensively exploited mainly towards cooling purposes [50].

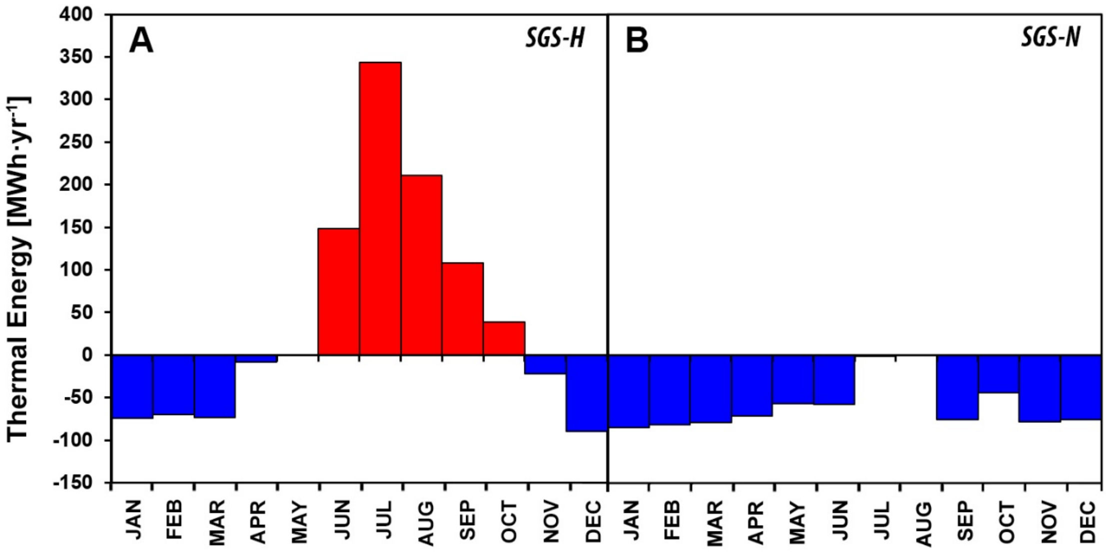

Figure 3. Thermal energy transferred by shallow geothermal systems SGS-H (**A**) and SGS-N (**B**) to the urban alluvial aquifer of Zaragoza.

3.2. Numerical Model Results

The 3D numerical modelling of groundwater and heat transfer allowed describing both the hydraulic and thermal impacts produced as a result of the host and nested GWHP systems operations. Figure 4 shows the calculated ground flow path lines after three years of operations. The flow path lines clearly describe how the pumping wells of the nested system (SGS-N) capture all the water discharged from the host system (SGS-H). Control points along a flow path line connecting the injection well of the host and the nested systems were considered to assess groundwater temperature evolution between injection and captation downgradient. Additionally, flow path lines also dismissed possible thermal shortcuts within each system's operation wells.

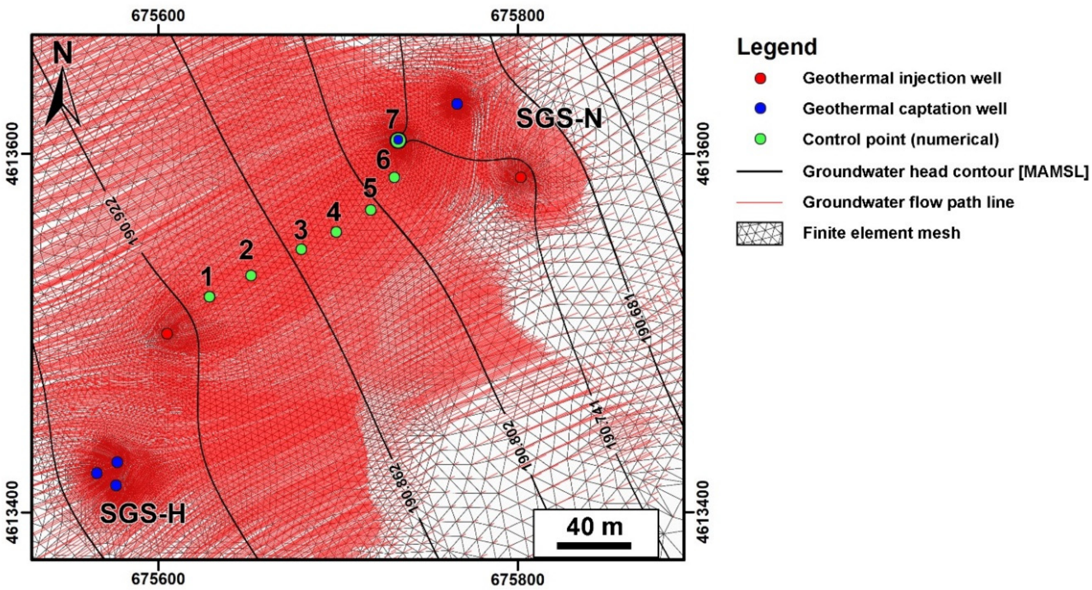

Figure 4. Groundwater flow path lines calculated by the numerical model.

The numerical solution to the heat transport problem showing groundwater temperature spatial distribution after three years of systems operations is presented in Figure 5. The thermal plume induced by the host system after 10 years of operation clearly impacts the two captation wells of the nested system. The hot plume generated by the host system encloses the nested system's cold plume generated downgradient. Furthermore, the nested cold plume prevents the 20 °C isotherm from advancing downgradient, thus significantly reducing thermal impact by the host system downstream.

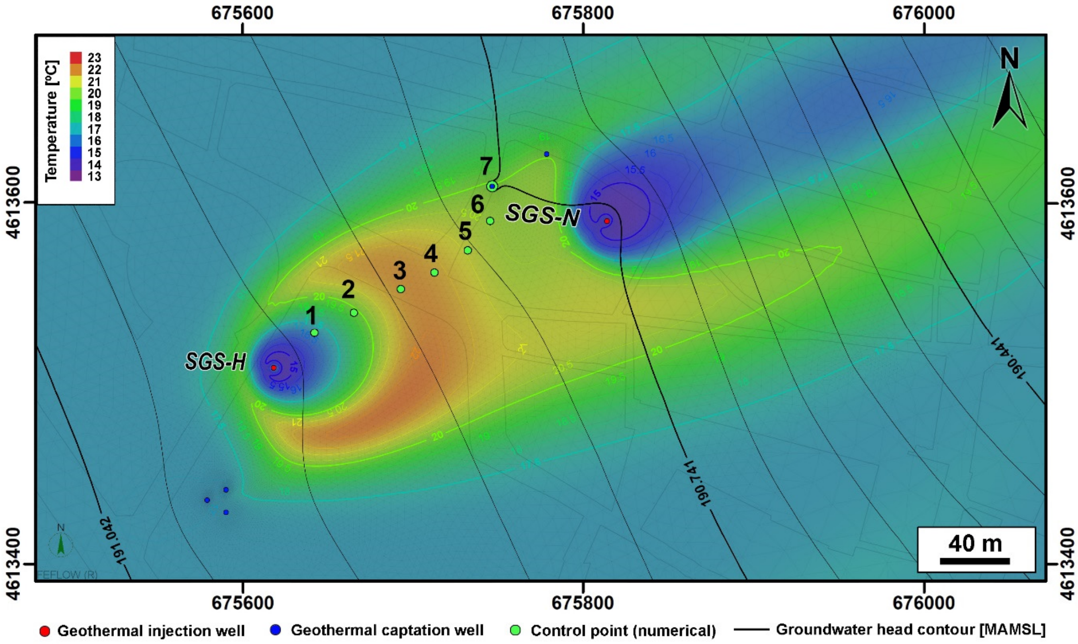

Figure 5. Calculated spatial distribution of groundwater temperatures after 10 years of exploitation. Piezometric map overlapped.

The propagation dynamics of the heat plume towards the captation well of the nested system can be inferred from Figure 6. This figure shows the calculated thermographs from seven control points between the host system discharge well and the closest nested system captation well, numbered 1 to 7, respectively (Figure 4). The thermographs for points 1, 2, and 3, which are located at 35, 65, and 95 m from the host discharge well, respectively, show temperatures below 17 °C (background temperature of the aquifer) only during the first year of exploitation. The maximum groundwater temperature amplitude oscillation is found, as expected, in the first control point. In the rest of the control points, oscillation amplitude is reduced as distance to the discharge well increases. Although the damping distance of the thermal plume is not reached [51], the oscillation in the captation well has a value of 0.56 °C in the third year of exploitation. Subsequently, the cooling-biased demand of the host system results in a hot plume where groundwater temperature is always above 19.8 °C after three years of exploitation at the control point 7, which corresponds to the captation well of the nested system. The peaks of the calculated thermographs present an additional delay and the curve becomes smoothed as the distance to the discharge well increases. From the second year of operation and henceforth, at all evaluated distances, the plume is strictly hot with positive impacts on the nested system, which is presenting a heating demand.

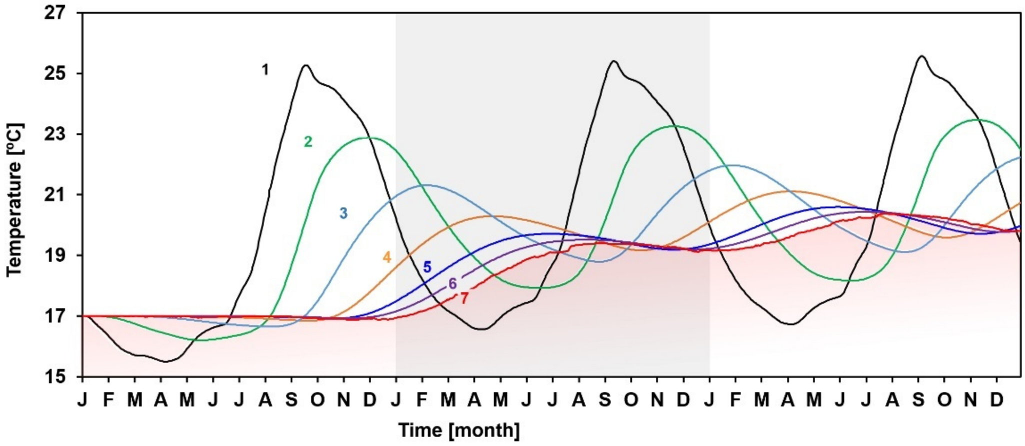

Figure 6. Calculated thermographs for groundwater temperature between the host and the nested system. Location of seven control points where thermographs were calculated are shown in Figures 4 and 5.

3.3. Nested Systems Implications on SGE Resource Management

The real SGE nested system investigated in this work supports the need for a multidimensional approach at different scales in order to reach an appropriate management of shallow geothermal systems [52]. The remediation effects produced by chilled water injection in urban aquifers were numerically described by Epting, Händel and Huggenberger [53] in the city of Basel (Switzerland), but here a real case study is presented and related to heated water injection. Without management policies, shallow geothermal systems can appear anywhere in urban space, interacting with other systems in different manners, depending on the distance between them. In the time dimension, considering large time scales, SGE systems continually appear and disappear. For this reason, it is necessary to take into account the existing installations, as well as those that may appear in the future and even those that existed, in order to explain the current and future thermal regime for the groundwater body managed. At a smaller time (and spatial) scale, a great transience in the thermal regime can be observed in response to an extremely variable exploitation regime. All this complexity highlights the need to approach the management of these geothermal systems by using numerical models at a city scale [26]. The use of 3D numerical models, together with the monitoring of shallow geothermal systems, has allowed identifying a symbiotic relationship between systems for the first time, i.e., positive thermal impacts between systems.

Derived from the real case here examined, it was described how a system spontaneously started to exploit a heat plume from another facility located upgradient. Therefore, knowing how and being able to reproduce the thermal regime of the aquifer allow, among other advantages [47], offering users the possibility to exploit existing thermal plumes. Promoting this type of activity will reduce the size of the thermal impacts, thus preventing the generation of subsurface heat islands and, in the last instance, producing the remediation of urban groundwater bodies thermally overexploited, as observed in the case investigated herein.

Nesting conditions for SGE systems targeted to exploit an already existing thermal plume will depend on the following aspects: (1) A stable-in-time host facility that guarantees the perpetuity of the resource, for example, an administration office building, as shown in this study case. (2) A clear bias in the host's energy balance. The greater the bias, the greater the geothermal potential for the nested system, provided that the bias and energy demand coincide. (3) The use of a combined cycle by the host system. If the host SGE system uses the aquifer for heating and cooling, then the thermal plume damping distance should be considered. The nested system must be placed at a suitable distance to obtain a stable temperature of interest, as verified in Figures 5 and 6.

The benefits for the host systems rely on the fact that the captation wells of the nested systems reduce the host systems' thermal plumes, thus decreasing the potential impacts on third party SGE systems. In addition, the demand load peaks of host systems, related to the nested systems' demand, will no longer be an issue and, therefore, the discharge temperatures will be able to exceed the general discharge threshold temperatures of the water body managed. Moreover, a nested system will react to the host biased demand with a much higher coefficient of performance, thus reducing its mechanical energy consumption, with the consequent economic and CO_2 emissions savings.

With regard to the possible adverse side effects, the symbiosis relationship between the two facilities can trigger a dependency between the two systems. The disappearance of one of the systems will require returning to unfavorable conditions. In the case a nested system is abandoned, the host system will not be able to make such aggressive use of the resources. On the other hand, if the host system ceases its activity, the nested system will not benefit from such favorable captation temperature conditions to meet its energy demand. Therefore, in either case, the possible adverse effects should be considered in advance to develop contingency plans, i.e., alternative response plans as well as feasibility studies of the alternative exploitation regimes.

4. Conclusions

The present work identified and examined for the first time a real case of nesting between shallow geothermal systems. This nesting process shows how a shallow geothermal system is able to absorb subsurface heat to satisfy its heating demand from an already existing hot thermal plume generated by an upgradient cooling-biased system. It is an example of a symbiotic relationship engendered by positive thermal interferences between two shallow geothermal systems. This newly identified relationship between shallow geothermal systems provides a novel vision of controlled thermal interferences between systems, which would be useful as a management measure in shallow geothermal energy resource governance. The described real case evidences the benefits for the managed groundwater body through this nesting system causing the energy transferred to the aquifer to be significantly reduced by up to two orders of magnitude, consequently withdrawing most of the thermal imbalance in global terms with respect to the aquifer. Furthermore, this type of practice is transferable to cities overlaying urban aquifers, which is the case for most of the large cities worldwide. The methods employed in this work provide a roadmap to city managers and environmental–water protection agencies concerned with the strategic use of water and geothermal resources to implement the decarbonization of the heating and cooling sectors. Furthermore, nesting practices of shallow geothermal resources can only be adopted under controlled conditions where hydrological and thermal regimes are understood. Finally, future research will need to cope with multiple nested systems and possible synchronization of heat plumes to exploit transient thermal plumes when thermal retardation is already known.

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Conflicts of Interest: None of the authors of this paper have any conflict of interest, including any financial, personal, or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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