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Novel management strategies for optimizing shallow geothermal energy exploitation: A European urban experience perspective

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ABSTRACT

The intensive exploitation of urban aquifers by shallow geothermal systems can affect the thermal balance of urban aquifers, thus reducing their renewability. This paper proposes a new management strategy for the sustainable use of shallow geothermal energy resources, based on imposing new constraints related to system exploitation regimes. To achieve this objective, a novel methodology was introduced for optimizing the operation of geothermal systems, by adjusting the flow rate and/or temperature change to maintain the existing thermal energy demand. The methodology was applied to a 1.8 million real operational data set from 24 shallow groundwater heat pump systems (GWHP), which are large and medium scale systems. The investigated GWHPs are located in five European cities. Two management alternatives for the optimization of geothermal energy resources use are presented in this work: (1) prioritizing higher flow rates over lower temperature changes, which tended to relatively decrease the discharge temperature by 1.48 °C on average, and (2) prioritizing higher temperature changes over lower flow rates, which tended to relatively decrease flow rates down to 8.09 L s^{-1} on average. The results show that GWHPs operating in European cities with the highest thermal power demand and flow rates achieved the highest flow rate reduction.

1. Introduction

The energy consumption for building heating and cooling in both the residential and industrial sectors presents a large impact on carbon emissions. According to the International Energy Agency (IEA), heating accounted for 40 % of global CO_2 emissions in 2018 [1]. Heating and cooling of buildings traditionally relies on the burning of fossil fuels, which creates a high energetic dependence on fossil fuel, and causes a significant increase in greenhouse gas emissions. The use of alternative energies, such as shallow geothermal energy, is crucial to avoid this issue [2,3].

Shallow geothermal applications include two types of systems: closed-loop systems (Ground Coupled Heat Pumps, GCHP) and open-loop systems (Ground Water Heat Pumps, GWHP). GCHP systems circulate a heat transfer fluid through a continuous loop of pipes buried in the ground, while GWHP systems use groundwater by means of at least two wells for pumping and injection [4–6]. In the case of GWHP systems, groundwater is the heat or cooling carrier fluid. GWHPs have several advantages; they are capable of delivering a greater energy output per unit of area and can sustain more consistent temperatures, provided they are designed correctly [7,8]. They also have lower construction costs compared to GCHPs, especially if the water table is close to the surface [9]. GWHP systems harness the constant temperature of groundwater, yet they are highly sensitive to thermal changes within the aquifer [9]. As acknowledged in the study by Bottcher et al., 2022 [10], the sealing of surfaces in urban areas is the most significant anthropogenic factor contributing to the overall warming of urban aquifers. However, GWHP systems induce temperature shifts in groundwater

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through the injection of hot or cold water, generating temperature anomalies in the aquifers, known as thermal plumes. Despite having a weaker influence on the thermal regime of the aquifer at a city scale compared to the surface sealing in urban aquifers [10], these thermal plumes can locally interact with nearby GWHP installations, thus causing a reduction in the system's efficiency or even its failure [11]. Many studies have been conducted around the world on the analysis of the influence of thermal plumes on urban aquifers, such as those performed in Basel (Switzerland), Zaragoza (Spain) [12]; Winnipeg (Canada) [13], Cardiff (United Kingdom) [14], Munich (Germany), Frankfurt (Germany), Karlsruhe (Germany) and Berlin (Germany) [15].

Two main types of thermal interferences can affect GWHP systems: (1) Intra-system thermal interference, which occurs when the heat exchange between the geothermal injection well and the ground creates a thermal anomaly in the subsurface that alters the thermal conditions of the production well of the same or a nearby GWHP system [16]; and (2) Inter-system thermal interference, which occurs when the production wells of different systems are influenced by each other. Other thermal interferences may occur due to the natural groundwater thermal regime, involving natural processes such as river-aquifer interaction [17], surface recharge or atmospheric temperature variation [18,19]. The Inter-system thermal interference can also be caused by human-induced changes, such as various types of groundwater use [20], or the interaction with urban subsurface infrastructures and building basements [10,18,21]. The exploitation of thermal use of groundwater can induce a thermal impact on aquifers [22], potentially altering their hydrogeological and ecological characteristics, compromising the original water chemistry [23,24], provoking corrosion or encrustations in equipment, creating thermal disturbances among adjacent geothermal systems [25], and exacerbating the heat island effect [26].

To achieve a more efficient and sustainable thermal use of groundwater and prevent the spread of thermal plumes, it is necessary to study and understand their behavior within the aquifer. To analyze thermal impacts of GWHP systems in urban aquifers, different simulation models have been developed: simplified (analytical) models [27–29] and numerical models [30]. Analytical models are computationally efficient, but they simplify the geometry and the initial and boundary conditions related to the aquifer properties, which restricts their applicability to complex problems. To overcome this limitation, numerical models are employed that incorporate hydraulic and thermal parameters, coupled physical processes, complex boundary conditions, and multiple subsurface layers, among other features. These parameters require a large amount of input data for the model, which enables the simulation of both the thermal and hydraulic effects of the GWHP systems in the aquifer, resulting in a more accurate representation of the thermal impacts. Some of the most relevant numerical models are those developed by Herbert et al. [31] for the urban aquifer of London, Böttcher, F. et al. [32], for the city of Munich, Mueller et al. [33] for the city of Basel, and García-Gil et al. [34] for the city of Zaragoza. However, development of numerical models able to adequately simulate the thermal and hydraulic conditions of aquifers is time-consuming and expensive and, therefore, are not commonly available.

Based on the development of both analytical and numerical models, optimization strategies are essential to maximize efficiency of GWHP systems and minimize the thermal and hydraulic impacts on the aquifers. These optimization strategies entail enhancing the design and functioning of GWHP systems, considering the location of the extraction and injection wells, the system efficiency (pumping rates and discharge temperatures) and the aquifer properties. The existent literature on GWHP optimization, however, is relatively scarce [30].

Park et al. (2020) [35] presented an optimization model based on a numerical model of groundwater simulation coupled with a genetic optimization algorithm, with the aim of optimizing the pumping rates of a single GWHP system. Subsequently, Park et al. [36] and Halilovic et al. [37,38] developed various optimization models aimed not only at optimizing pumping rates but also determining the ideal well locations.

These studies represent a remarkable progress in the optimization of shallow geothermal systems, as they propose innovative methods that integrate analytical models of groundwater flow into the optimization. However, all of them simulate hypothetical wells in environments predetermined by the algorithm developed. Thus, they do not address the concept of managing the already existing GWHPs at city scale, as they are focused on determining the optimal positions of the GWHPs. Often, these facilities have already been built, so that establishing a new one is not viable. The only viable alternative is to regulate the exploitation regime strategy, that is, to regulate the flow rates and discharge temperatures (DT) of each installation to optimize GWHPs' operation and reduce the thermal impact on the aquifer.

The literature on the administration, prevention or minimization of thermal interferences between already installed GWHPs is also relatively limited [30]. Some of the studies that tackle this issue were performed by García-Gil et al. [39], who suggested the thermal management concept of "relaxation factor" for the new GWHP systems in Zaragoza. Epting et al. [12] applied this concept in Basel and compared the outcomes with those found at Zaragoza. Attard et al. [40] delineated thermal protection perimeters around the extraction wells of GWHPs; and García-Gil et al. [41] calculated a balanced sustainability index for each GWHP. These studies concentrate on the installation of individual systems, to diminish interferences with other GWHPs. However, they do not directly investigate the effect of increasing the temperature changes and reducing the flow rates, or increasing the flow rates while reducing the temperatures changes, as a specific management strategy. The thermal management of GWHPs is directly related to the facilities themselves, as well as the thermal and hydraulic properties of the aquifer. To date, no alternative proposals have been proposed for managing flow rates and discharge temperatures that maintain the existing energy for cooling and heating demand.

Therefore, the aim of this work is to propose a new optimization model for the management of the GWHPs that already exist in an urban area, and whose location cannot be modified. In this study, we propose a management approach for GWHP systems based on adjusting the thermal regimes of the individual systems, while maintaining unchanged heating and cooling loads and adhering to user-defined thresholds and environmental or regulatory limits (e.g. aquifer manager or water authority). The approach offers two optimization options: the first aims to maximize the injection-production flow rate, and the second seeks to maximize the discharge temperature. This method is universally applicable to any cluster of GWHP systems across diverse hydrogeological environments. To demonstrate its effectiveness, the proposed optimization method was tested using real operating data from 24 GWHPs across five European cities (Fig. 1).

The results of this study are expected to provide scientific and technical criteria to authorities facing thermal interferences between managed GWHPs, as well as adequate tools to make informed decisions for a more sustainable implementation of GWHPs in cities. All this together will allow the efficient use of shallow geothermal resources.

2. Data and methods

2.1. Selected shallow geothermal systems in Europe

The study covered a total of 24 GWHPs located in five shallow urban aquifers across Europe (Fig. 1), each with its own climatic, geographical, and hydrogeological characteristics that influence their exploitation potential. The selected cities were Zaragoza, Ljubljana, Munich, Basel, and Cardiff, all of them located above alluvial aquifers. A brief overview of the main climatic, geographical, and hydrogeological settings of each site is provided in Table S1.

The cooling and heating energy demand of each city was calculated by applying the indices of Cooling Degree Days (CDD) and Heating Degree Days (HDD) [42,43]. These indices quantify the deviation of the average daily temperature from a base temperature considered

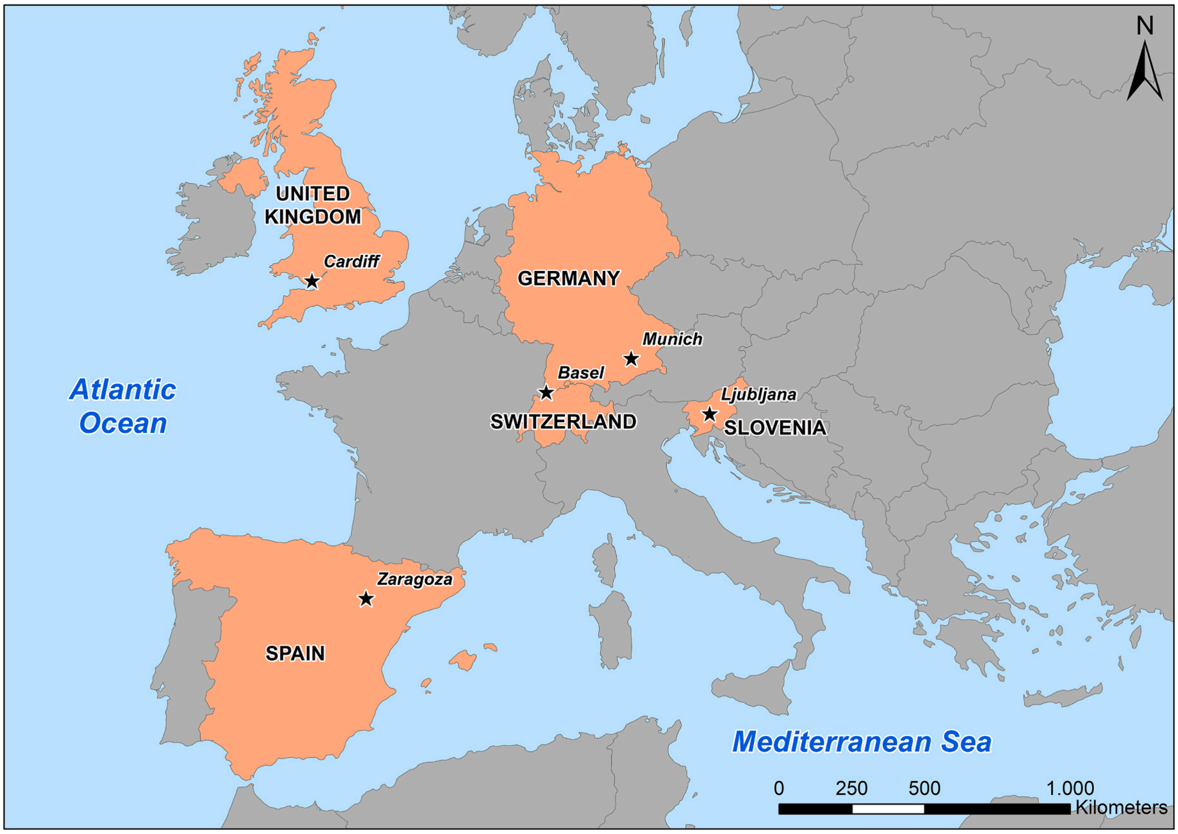

Fig. 1. Location of the investigated GWHP systems in the five considered cities of Europe.

comfortable (concretely, 18 °C), capturing both the intensity and duration of external temperatures. The CDD and HDD were calculated using the daily average temperature (T_C) in °C of the last four years (2019–2023). The daily temperatures were recorded at weather stations near to GWHPs (Table 1). The HDD_{year} and CDD_{year} were defined as follows:

$$HDD_{year} = \sum_{days} \max(0, (18 - T_C)) \quad (1)$$

$$CDD_{year} = \sum_{days} \max(0, (T_C - 18)) \quad (2)$$

According to these definitions, Zaragoza is the city requiring the most cooling for its buildings, due to the high temperatures in summer, with an average of 973 Cooling Degree Days (CDD) over the last five years. On the other hand, Cardiff is the city requiring the least cooling for buildings in summer, with only 92 CDD, due to the moderate temperatures existing in summer. Munich and Ljubljana are the cities whose buildings require the most heating for winter, with 3252 and 3173 Heating Degree Days (HDD), respectively. In contrast, Zaragoza and Cardiff require the least heating in winter, with 1566 and 2491 HDD, respectively (Table 1). Globally, Zaragoza requires less heating for its buildings, as this city presents the least rainfall rate and, therefore, receives the greatest amount of sunshine. In Cardiff, moderate temperatures are observed all year round.

2.2. Data acquisition

This study examined 24 GWHP systems situated in five European cities, with a total of 1.8 million temperature measurements from 2013 to 2023 (the full range of available data) (Table 2). The applications of the GWHP systems are cooling, heating or both (dual mode). The selected GWHP systems are those with extensive monitoring data available (high resolution monitoring). However, this does not necessarily represent the usage patterns of the aquifer system at large. 12 GWHPs operating in dual mode were found exclusively in Zaragoza, showing an urban use for building air-conditioning, and a 15-min recording interval. Seven GWHPs operating in single mode for heating purposes were found in Ljubljana (5), Basel (1), and Cardiff (1), all of them showing an urban use and 15-min or daily recording intervals. Finally, five and two GWHPs operating in single mode for cooling purposes and industrial use were found in Basel (3) and Munich, respectively, and they presented a daily or hourly recording interval.

Table 1
Climate data and comparison of the heating and cooling loads of Zaragoza, Ljubljana, Munich, Basel, and Cardiff. Climate data was obtained from Historical series of: Zaragoza: 1981–2023, Ljubljana: 1991–2021, Basel: 1991–2021, Munich: 1990–2023, Cardiff: 1991–2021 [44–46].

City	Average annual temperature (Historical series) [°C]	Average minimum monthly temperature (Historical series) [°C]	Average maximum monthly temperature (Historical series) [°C]	Cooling degree days (CDD) (Average of the last 5 years)	Heating degree days (HDD) (Average of the last 5 years)
Zaragoza	16.4	7.2 (January)	25.6 (July)	973	1566
Ljubljana	11.7	1.2 (January)	21.9 (July)	384	3173
Basel	8.6	2.3 (January).	20.3 (July)	404	2622
Munich	11.2	−0.5 (January)	18.6 (July)	291	3252
Cardiff	10.5	5 (February)	16 (August)	92	2491

Table 2
Compilation of the main characteristics of each GWHP system.

City	Label	System usage	Active monitoring		Monitored period [d]	Number of measurement	Measurement frequency
			Start	End			
Zaragoza	ZGZ-01	Cooling-heating buildings	February 10, 2017	July 16, 2020	1252	120,192	15-min
	ZGZ-02	Cooling-heating buildings	November 10, 2016	December 31, 2020	1496	143,616	15-min
	ZGZ-03	Cooling-heating buildings	March 1, 2017	May 31, 2022	1917	184,032	15-min
	ZGZ-04	Cooling-heating buildings	February 10, 2017	February 28, 2020	1113	106,848	15-min
	ZGZ-05	Cooling-heating buildings	January 3, 2017	November 30, 2019	696	66,816	15-min
	ZGZ-06	Cooling-heating buildings	November 20, 2019	January 01, 2021	408	39,168	15-min
	ZGZ-07	Cooling-heating buildings	July 6, 2017	August 31, 2019	786	75,456	15-min
	ZGZ-08	Cooling-heating buildings	July 1, 2017	October 26, 2021	1578	151,488	15-min
	ZGZ-09	Cooling-heating buildings	August 4, 2017	August 5, 2021	731	70,176	15-min
	ZGZ-10	Cooling-heating buildings	February 02, 2016	March 31, 2022	2249	215,904	15-min
	ZGZ-11	Cooling-heating buildings	January 8, 2019	April 30, 2022	1208	115,968	15-min
	ZGZ-12	Cooling-heating buildings	September 11, 2016	April 25, 2022	2052	196,992	15-min
Ljubljana	LIU-1	Heating buildings	September 1, 2022	March 23, 2023	203	19,488	15-min
	LIU-2	Heating buildings	September 1, 2022	March 23, 2023	203	19,488	15-min
	LIU-3	Heating buildings	September 1, 2022	March 23, 2023	203	19,488	15-min
	LIU-4	Heating buildings	September 1, 2022	March 23, 2023	203	19,488	15-min
	LIU-5	Heating buildings	September 1, 2022	March 23, 2023	203	19,488	15-min
Basel	BAS-01	Cooling (industrial)	December 30, 2016	December 30, 2021	1826	1826	Daily
	BAS-02	Cooling (industrial)	January 01, 2017	November 30, 2022	2192	2192	Daily
	BAS-03	Cooling (industrial)	December 31, 2016	February 3, 2022	1860	1860	Daily
	BAS-04	Heating buildings	December 31, 2016	May 3, 2022	1949	1949	Daily
Munich	MUC-1	Cooling (industrial)	January 01, 2013	May 1, 2014	485	11,640	Hourly
	MUC-2	Cooling (industrial)	January 01, 2013	May 1, 2014	485	11,640	Hourly
Cardiff	CDF-1	Heating buildings	February 17, 2016	July 11, 2020	1606	154,176	15-min

2.3. Optimization of flow rates and discharge temperatures

The proposed adjustment method was based on the existing relationship between the thermal power usage in the GWHPs (H) [W], the pumping/injection flow rate (Q) [$m^3 \cdot s^{-1}$] and the temperature change (ΔT) [K]. The temperature change was obtained by subtracting discharge temperature T_2 [K] from production temperature T_1 [K]. Thermal power was calculated as the energy transferred to the aquifer in a period of time between two consecutive measurements of flow rate, discharge temperature and production temperature, as follows:

$$\mathrm{H} = Q \cdot C_w \cdot \rho_w \cdot (T_2 - T_1) \tag{3}$$

Where C_w (4182 J $kg^{-1} \cdot K^{-1}$) is water heat capacity and ρ_w (998 kg m^{-3}) is water density.

This fact implied two regulation scenarios: one where the discharge temperature was adjusted by increasing the flow rate, and another one where the flow rate was adjusted by raising the discharge temperature. The workflow in Fig. 2 schematically shows the steps necessary for a correct development of the optimization.

The first scenario, based on the regulation of the discharge temperature, was obtained by increasing the flow rate to the user's chosen value, in this case, a real operation value. The chosen value was twice the value of the real exploitation flow rate (2Q), while maintaining the energy demand. When the new flow rate value surpasses the highest historical value recorded, known as (Q_{max}), the system gets adjusted by limiting the flow rate to Q_{max}. From the new flow rate value obtained, the discharge temperature (T_2) was recalculated by substituting Q with the newly calculated flow rates. Consequently, (T_2) was obtained by solving Eq. (3).

The second scenario involves regulating the flow rate by increasing the discharge temperature to improve the system's flow capacity. The temperature change was obtained based on their current mode of operation, which can be heating mode (HM), cooling mode (CM) or dual mode (DM) (switching between heating and cooling as needed). In cases where the GWHP is capable of dual operation, the flow rate is regulated accordingly to match the operation mode of any given time.

If the temperature change was less than zero ($\Delta T < 0$), the GWHP was considered to be operating in heating mode. For the heating mode optimization, the minimum value of the discharge temperature was set according to the measured minimum value recorded by the GWHP. The minimum discharge temperature value was referred to as $T_{2\mathrm{HM0}}$, and replaced T_2 ($T_2 = T_{2\mathrm{HM0}}$). If the temperature change was above zero ($\Delta T > 0$), the GWHP was considered to be working in cooling mode. This value was referred to as $T_{2\mathrm{CM0}}$, and replaced T_2 ($T_2 = T_{2\mathrm{CM0}}$).

Based on this calculated discharge temperature, and maintaining the thermal power used in the installation (H), the new flow rate Q_{THM0} (if the GWHP was working in heating mode) or Q_{TCM0} (if the GWHP was working in cooling mode), was recalculated using the following formula derived from Eq. (3):

$$Q_{\mathrm{THM0}}, Q_{\mathrm{TCM0}} = \frac{\mathrm{H}}{C_w \cdot \rho_w \cdot (T_{2\mathrm{HM0}}, T_{2\mathrm{CM0}} - T_1)} \tag{4}$$

When the recalculated flow rates (Q_{THM0}, Q_{TCM0}) exceeded the maximum recorded value of the GWHP, an iterative subtraction loop was executed at each iteration that reduced $T_{2\mathrm{HM0}}$ by 0.0025 until the maximum recorded value of ($Q_f\mathrm{HM}, Q_f\mathrm{CM}$) was reached. The iterative subtraction was executed by 0.0025, as this value was the minimum to perform a viable iterative operation without making the computational cost unfeasible, until the maximum recorded value was reached, as

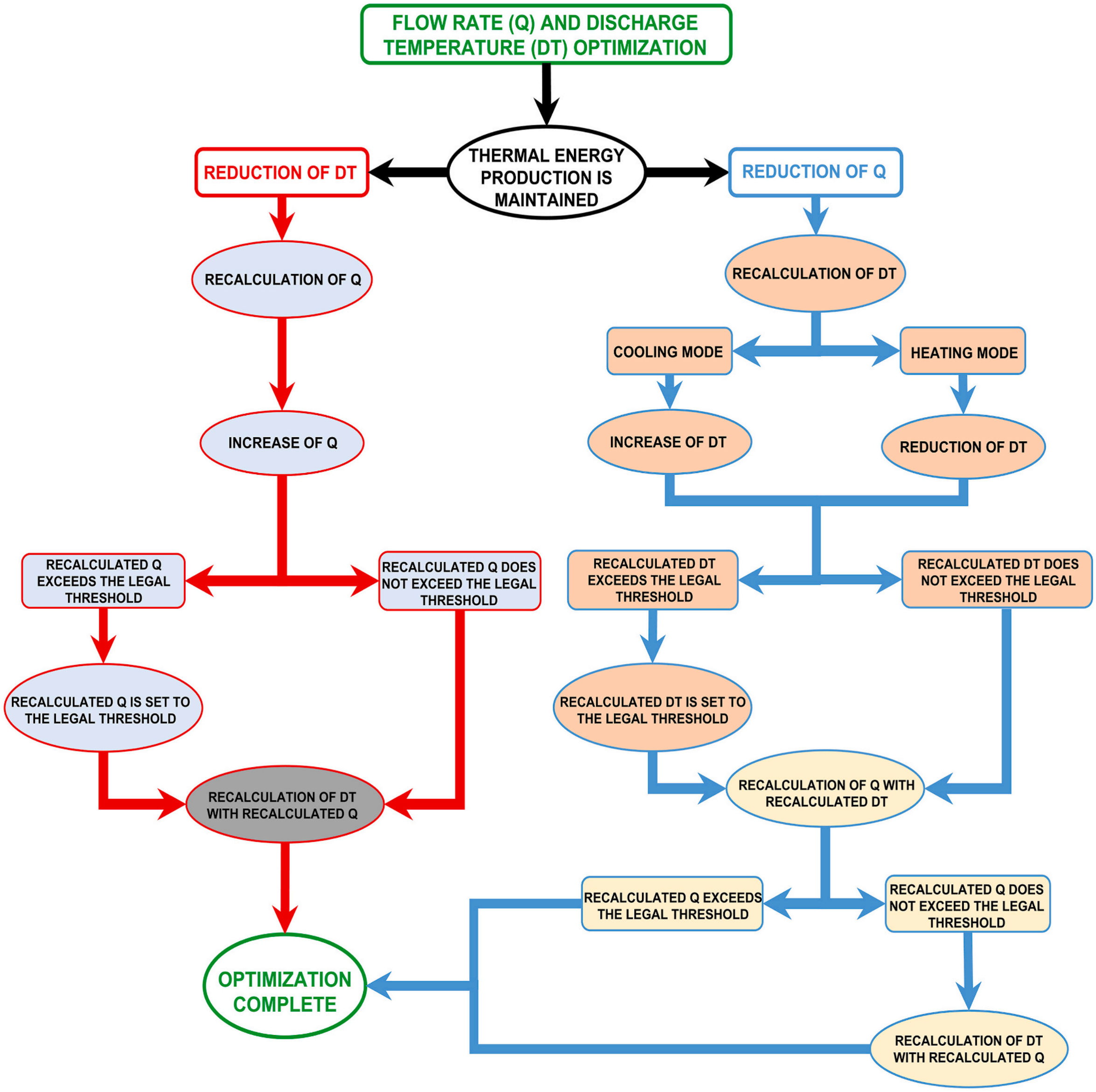

Fig. 2. Workflow of the flow rate (Q) and discharge temperature (DT) optimization.

follows:

$$T_{2^n}HM, T_{2^n}CM = T_{2_{n-1}} - 0.0025\ (n \in \mathbb{N}, n \geq 1) \tag{5}$$

Where n is a natural number ≥ 1. The condition for this iterative subtraction implied that the recalculated discharge temperature at each iteration ($T_{2^n}HM$, $T_{2^n}CM$) should never exceed the minimum or maximum value established by the regulatory authorities ($T_{2n} > T_{2HM0}$, $T_{2n} < T_{2CM0}$). Based on this newly calculated discharge temperature ($T_{2f}HM$, $T_{2f}CM$), the new flow rate (Q_fHM, Q_fCM) was obtained using the following equation:

$$Q_fHM, Q_fCM = \frac{H}{C_w \cdot \rho_w \cdot (T_{2f}HM, T_{2f}CM - T_1)} \tag{6}$$

For this study, the maximum and minimum values of discharge temperature, and the maximum value of flow rate recorded by the GWHP were used. Nonetheless, the maximum and minimum values can be replaced by user values according to the current legislation.

3. Results and discussion

3.1. Temperature change and flow rate constraints on thermal power

To illustrate the application of the proposed methodology, the relationship between thermal power, flow rate, and temperature change is shown. The graph in Fig. 3 displays maximum equivalent flow rates and temperatures for the same historical maximum thermal power, recorded by the GWHP ZGZ-06 system, in both heating and cooling modes. This graph shows how an increase in temperature change significantly reduces the flow rate needed to operate the GWHP ZGZ-06 system while maintaining power, and vice versa. This GWHP system recorded 39,168 measurements of flow rate and discharge temperatures every 15 min between November 20, 2019 and January 01, 2021 (Table 2).

The thermal power values were displayed according to the quartiles and maximum values of the thermal power data recorded by the GWHP (Table 3). These thermal power values were depicted using potential lines that relate the flow rate to the temperature change required, while maintaining power as a function of increasing temperature and flow rate change by solving Eq. (3).

Fig. 3 was not designed for the study of new GWHP systems. If a pre-

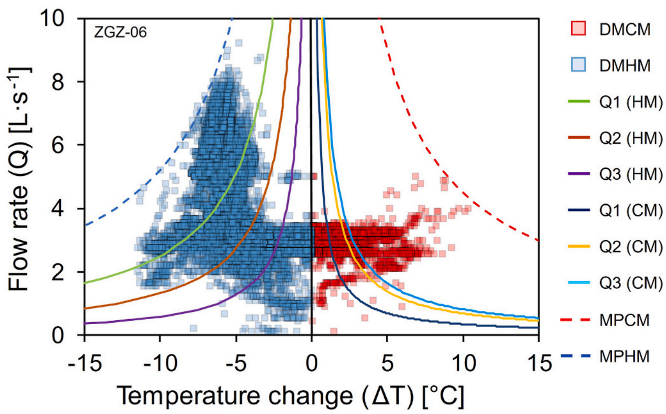

Fig. 3. Relationships between thermal power, flow rate, and temperature change recorded in the ZGZ-06 GWHP system. Data measured in cooling mode (DMCM); Data measured in heating mode (DMHM); Maximum power in cooling mode (MPCM); Maximum power in heating mode (MPHM). Q1, Q2, Q3 represent the thermal power quartiles.

Table 3
Quartiles and peak thermal power consumption in heating and cooling mode.

Maximum thermal power	Quartile thermal power 1 (Q1)	Quartile thermal power 2 (Q2)	Quartile thermal power 3 (Q3)
Heating mode [J s^{-1}]			
$-2.23 \cdot 10^8$	$-1.09 \cdot 10^8$	$-5.92 \cdot 10^7$	$-2.85 \cdot 10^7$
Cooling mode [J s^{-1}]			
$1.87 \cdot 10^8$	$1.45 \cdot 10^7$	$2.88 \cdot 10^7$	$3.42 \cdot 10^7$

established operating scenario is set, it is possible to set a maximum thermal power and offer maximum equivalent flow rates and temperatures for that specific power. This graph can also be used to monitor that the installation does not exceed a pre-established maximum power limit. There is no minimum data range required to obtain graphical results, as a historical maximum thermal power of use is established. However, to carry out a reliable study, it is recommended to constantly monitor the GWHP system.

3.2. Adjustment of flow rate and discharge temperature to optimize the use of GWHP systems

Based on the optimization methodology and the graphical relationship illustrated in Fig. 3, an optimization methodology for the use of GWHP systems, involving the adjustment of flow rate and discharge temperature, is proposed, with the aim of reducing the thermal impact of GWHP systems on urban aquifers. The model was applied to the 24 GWHP systems with different use modes and energy demands (Table 2). The optimization methodology was based on adapting the system's operation to meet the thermal power demand, flow rate and discharge temperatures obtained from the historical records of the GWHPs studied. Thus, optimal flow rate values and optimal discharge temperature range values can be proposed (Table 4).

Three types of optimizations were proposed, based on the GWHPs' intended use: Cooling Mode (CM), Heating Mode (HM) or Dual Mode (DM). Each optimization was constrained by the maximum and minimum values of flow rate allowed by the heat pump, and the discharge temperature limitation, depending on the objective and thermal/hydraulic environmental constraints of each GWHP.

3.2.1. Dual mode (cooling-heating mode)

Dual GWHP systems are only used in the city of Zaragoza (ZGZ-01 – ZGZ-12), due to the large thermal range between winter and summer months. In the rest of the European cities studied, there also exist GWHP systems operating in dual mode; however, no extensive monitoring data is available. 12 GWHP systems with different flow rates and discharge temperatures were examined and optimized (Fig. 4). This type of GWHP is the best suited for a city like Zaragoza, as shown in Table 1, where the heating and cooling demand accounts for 58 % and 41 % days in the year, respectively. This type of GWHP shows a big versatility for the thermal management of the aquifer, as there are solutions based on thermal recycling, which regulate the base temperature of the aquifer throughout the year [20,23]. Thermal recycling is a solution proposed at the entire aquifer level, but the different thermal interactions between GWHPs have not yet been considered when they operate simultaneously [20,47]. Therefore, adjusting the flow rate or the temperature is essential to control the formation and spread of the thermal plumes generated by the GWHPs, and their interaction with other GWHPs, which can cause a decrease in the system's performance. This optimization methodology could assist in the management of the thermal impact on the aquifer, by providing exploitation alternatives without compromising the energy demand. The model could be calibrated based on a thermal recycling study, offering alternatives based on injection temperatures and the calculation of the required flow rate to avoid compromising the demand.

Table 4
Maximum and minimum limit values applied to the methodology for Q, discharge temperature (DT), and H.

Label	Maximum Flow rate (Q) [L s^{-1}]	Maximum Temperature (DT) [°C]	Minimum Temperature (DT) [°C]	Maximum Power (H) [J s^{-1}]
ZGZ-01	26.3	40.00	10.70	$1.20 \cdot 10^9$
ZGZ-02	62.46	35.60	6.90	$2.19 \cdot 10^9$
ZGZ-03	99.00	28.40	11.80	$2.92 \cdot 10^9$
ZGZ-04	5.30	32.26	9.84	$1.60 \cdot 10^8$
ZGZ-05	47.62	27.80	14.00	$1.19 \cdot 10^9$
ZGZ-06	9.22	28.34	6.20	$2.23 \cdot 10^8$
ZGZ-07	20.00	26.40	10.00	$7.52 \cdot 10^8$
ZGZ-08	155.04	44.50	16.66	$9.25 \cdot 10^9$
ZGZ-09	17.81	41.94	10.13	$3.66 \cdot 10^8$
ZGZ-10	63.33	37.90	8.30	$2.36 \cdot 10^9$
ZGZ-11	63.30	37.30	8.60	$9.59 \cdot 10^8$
ZGZ-12	23.31	45.00	7.11	$1.15 \cdot 10^9$
LIU-1	12.22	14.09	9.44	$1.51 \cdot 10^8$
LIU-2	6.21	16.58	10.10	$1.67 \cdot 10^7$
LIU-3	12.12	25.64	7.90	$2.18 \cdot 10^8$
LIU-4	9.89	19.33	9.44	$8.40 \cdot 10^7$
LIU-5	6.67	13.34	10.64	$4.42 \cdot 10^7$
BAS-01	12.01	18.09	15.92	$1.61 \cdot 10^8$
BAS-02	10.11	22.07	14.03	$1.61 \cdot 10^8$
BAS-03	9.03	18.69	11.78	$7.52 \cdot 10^8$
BAS-04	12.18	15.01	11.58	$1.23 \cdot 10^8$
MUC-1	87.29	18.04	12.00	$7.96 \cdot 10^9$
MUC-2	177.57	17.99	12.07	$3.60 \cdot 10^9$
CDF-1	2.00	12.30	6.80	$1.20 \cdot 10^7$

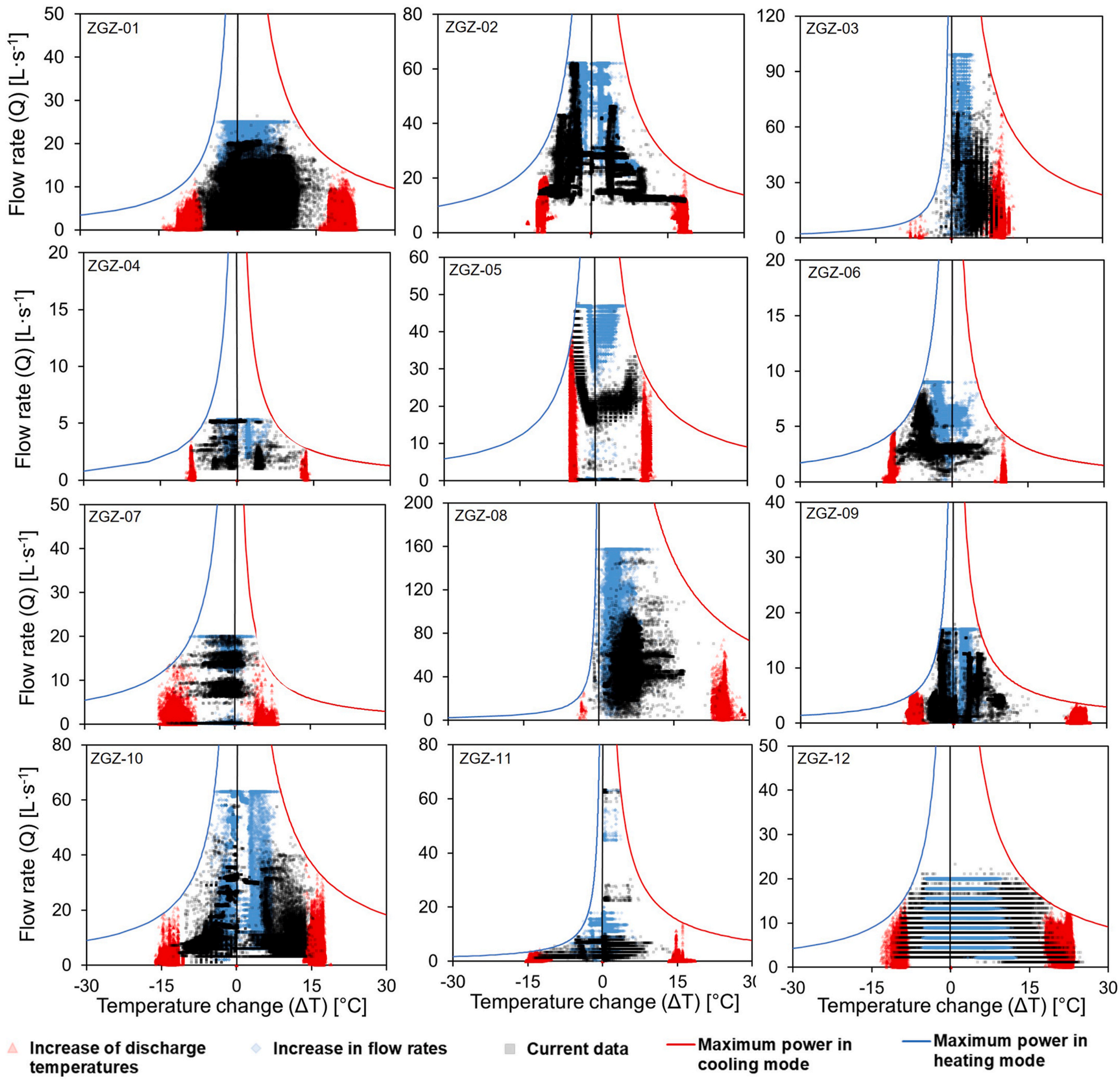

Fig. 4. Optimized GWHPs ZGZ-01 - ZGZ-12 in dual operating mode. Maximum power in cooling mode (MPCM); Maximum power in heating mode (MPHM).

3.2.2. Heating mode

The optimization methodology was applied to seven GWHP systems operating in heating mode (Fig. 5), located in the cities of Ljubljana, Cardiff and Basel (Table 2). The three cities have an average heating demand of 270 (Ljubljana), 210 (Cardiff) and 240 (Basel) days per year, which account for 74 %, 58 % and 66 % days of a year, respectively. These GWHPs have different measurement intervals, as shown in Table 2. The maximum thermal loads, the minimum temperatures and the maximum flow rates were used as limiting factors, except for GWHP CDF-01, where the current operating flow rate (4 L s^{-1}) was doubled, as it had a constant flow rate of 2 L s^{-1}. This increase was adjusted according to the corresponding temperatures to maintain the maximum thermal power demand. The graphical optimization methodology was independent of the measurement interval in the data. The results show positive temperature changes, always below 2 °C, which implies that the GWHPs operated at an exploitation regime without the system being in operation. Consequently, despite the presence of some positive temperature readings, the GWHP systems were only functional for heating purposes. This optimization processes all raw data, and has the potential to simultaneously optimize values for both cooling mode (positive temperature change) and heating mode (negative temperature change). For this reason, low temperature and flow MPHM limits are observed. Even though these GWHP systems are not operating in cooling mode, they have positive temperature change values, which are optimized as if they were heating mode operating values. This occurs despite the fact that these values indicate the GWHP systems pumped water without the heat pump being in operation.

3.2.3. Cooling mode

The optimization methodology was applied to three GWHPs in Basel

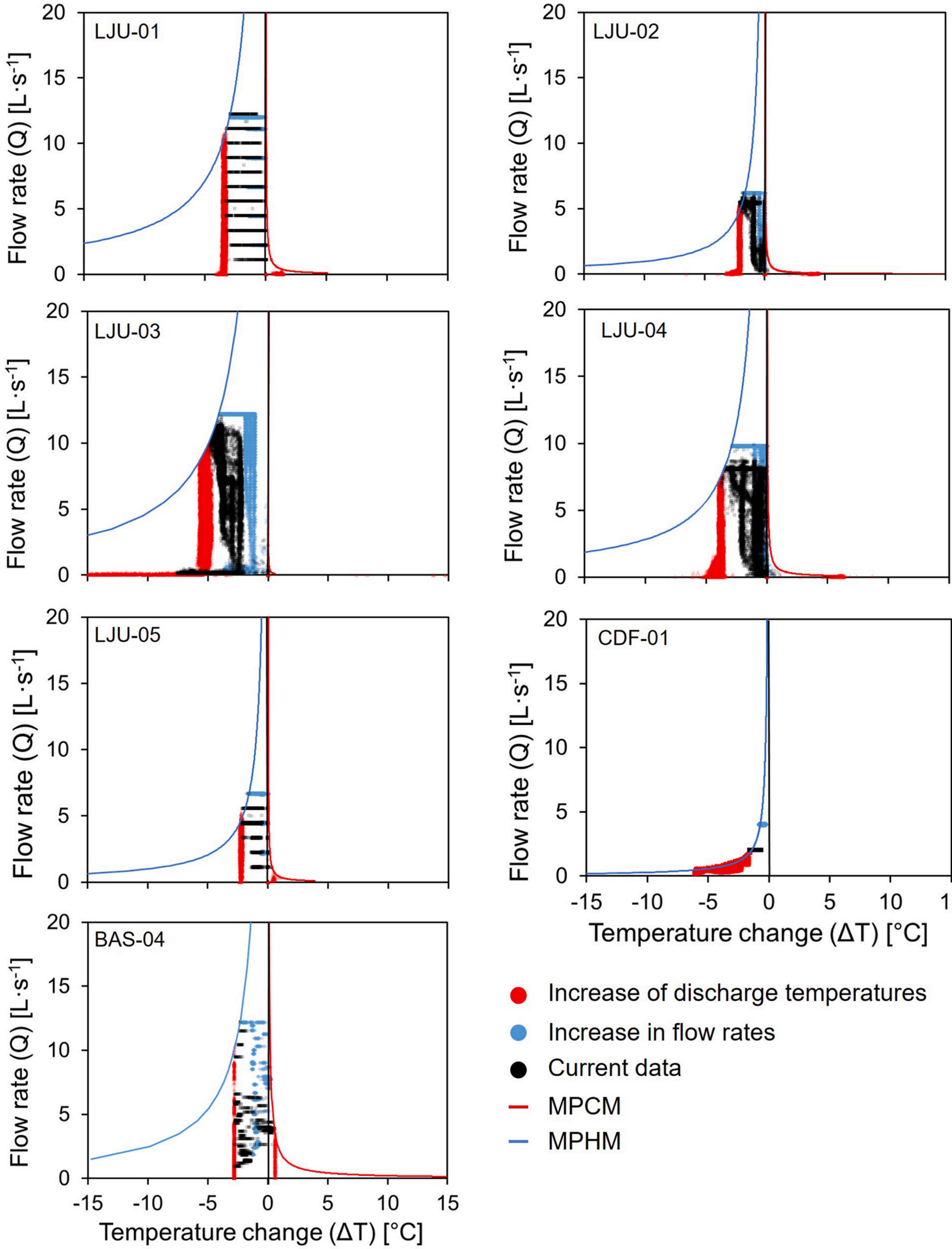

Fig. 5. Optimized GWHPs LJU-01, LJU-02, LJU-03, LJU-04, LJU-05, CDF-01, and BAS-04 in heating operating mode. Maximum power in cooling mode (MPCM); Maximum power in heating mode (MPHM).

(BAS-01, BAS-02 and BAS-03) working in cooling mode, together with two GWHPs in Munich (MUC-01 and MUC-02) operating as an industrial cooling system. The results of the BAS-02 and BAS-03 GWHPs reflected negative temperature changes (ΔT), always lower than −2 °C. Therefore, although some negative data were observed and calibrated by the optimization methodology in HM, they were considered GWHPs intended for cooling. This optimization offered two different regulation alternatives: increasing the flow rate or increasing the discharge temperature. Increasing the flow rate injected reduced the discharge temperature exponentially, as shown in Fig. 6. Depending on the flow rate and temperature, the aquifer could be affected by increasing or changing the direction and interactions between the thermal plumes produced by the GHWPs. In addition, alternative exploitation approaches may be required, such as increasing the discharge flow rate and

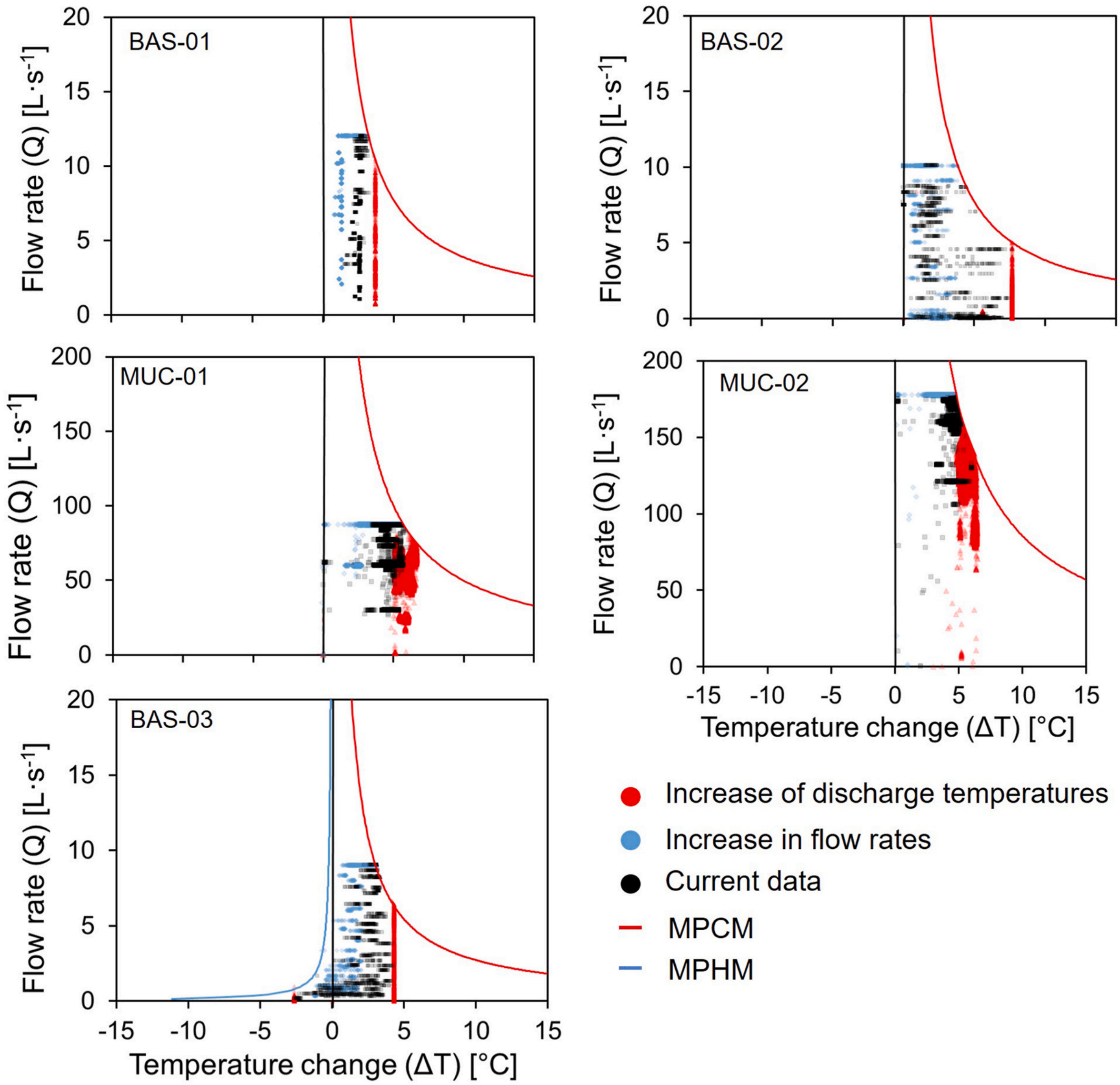

Fig. 6. Optimized GWHPs BAS-01, BAS-02, BAS-03, MUC-01 and MUC-02 in cooling operating mode. Maximum power in cooling mode (MPCM); Maximum power in heating mode (MPHM).

decreasing the temperature, or decreasing the flow rate and increasing the temperature [48]. The results of the GWHP BAS-03 showed negative temperature changes, always less than 2 °C, which implied it was operating in heating mode without the system being in operation. Consequently, despite the presence of some negative temperature readings, this GWHP system was only operating for cooling. This optimization processes all raw data and has the potential to simultaneously optimize both values from cooling mode (positive temperature change) and heating mode (negative temperature change). For this reason, low temperature and flow MPCM limits were observed, because although this GWHP system does not operate in heating mode, it has negative temperature change values. These values are optimized as if they were heating mode operating values, despite indicating that this GWHP system was pumping water without it being in operation.

3.3. Thermal impact improvement after using the optimization method

The average measured Q and ΔT values were compared with the average values obtained from the optimization (Figs. 7 and 8). The optimization results shown in Table S2 demonstrate the improvement potential for each GWHP in terms of flow rate (Q), and positive and

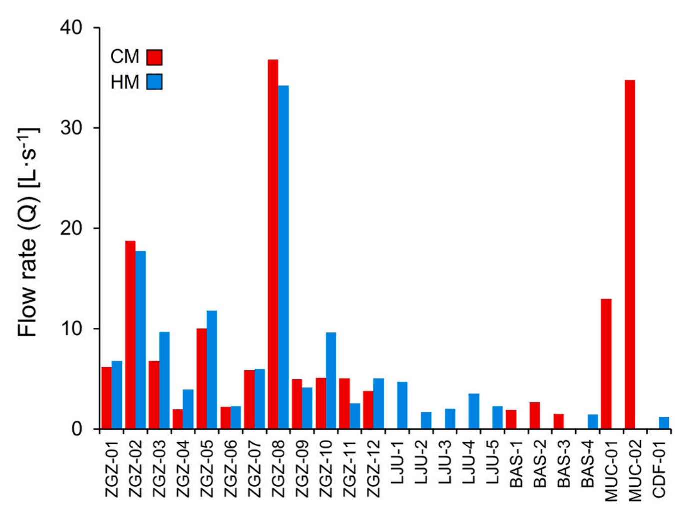

Fig. 7. Potential reduction of Q in heating mode (HM) and cooling mode (CM).

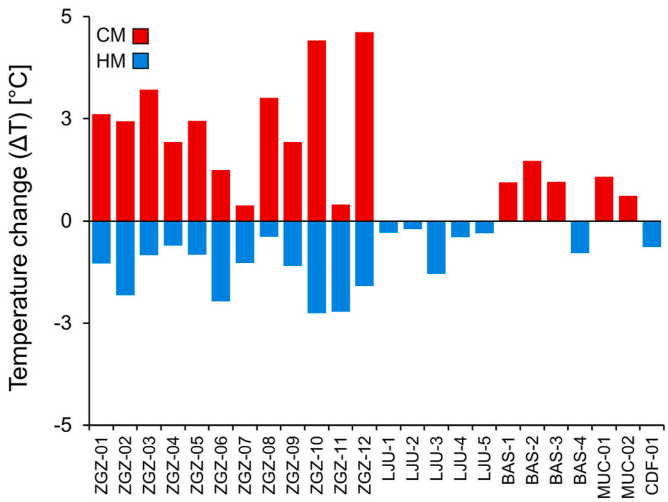

Fig. 8. Potential reduction of ΔT in cooling mode (CM) and heating mode (HM).

negative discharge temperature.

Increasing the temperature changes and reducing the flow rates led to a decrease in the flow rates of all GWHP systems, down to an average of 8.09 L s^{-1}. The GWHPs that had the highest potential for optimization of flow rate in cooling mode were ZGZ-08, ZGZ-02 and ZGZ-05, with reduced flow rates higher than 9 L s^{-1} (Fig. 7). The GWHPs with the highest flow rate optimization potential operating in heating mode were ZGZ-02, ZGZ-05, ZGZ-03, ZGZ-08 and ZGZ-10, with reduced flow rates greater than 9 L s^{-1} (Fig. 7).

Increasing the flow rate and reducing temperature changes resulted in an average reduction of 1.48 °C in the discharge temperature for all GWHP systems. The GWHPs that had the highest potential for optimizing temperature change in cooling mode were ZGZ-03, ZGZ-08, ZGZ-10 and ZGZ-12, with ΔT values reduced to less than −3 °C. In heating mode, the GWHPs with the highest ΔT optimization potential were ZGZ-10, ZGZ-11, ZGZ-06, ZGZ-02 and ZGZ-12, with ΔT values reduced to less than −1.5 °C (Fig. 8).

The results showed that the European cities that achieved the greatest reduction in flow rate (Q) were those operating with higher thermal power and the higher flow rate. This can be attributed to the regulatory framework, which limits the options for temperature variation.

Fig. 9 shows the final adjustment results of flow rates and temperature changes for the 24 GWHP systems. The results indicate that certain GWHPs can significantly reduce flow rates and thermal impacts by modifying their operational parameters. The GWHPs with the greatest margin of improvement are those operating in DM (Fig. 9). On the other hand, there were other GWHPs that only worked in HM or CM, which were already optimized or had very little room for improvement. They operated with low Q and ΔT. This limitation in improvement was a result of a constraint caused by the power limitation, since improvement occurred exponentially at higher Q and ΔT. GWHPs operating in DM took advantage of thermal recycling cycles to increase or decrease their temperatures depending on seasonality, which is why their optimization potential was higher.

The proposed optimization methodology represents a significant advance in terms of regulating systems intended for geothermal use, as a major challenge for this type of GWHPs is the thermal interference between them [16,48,49] and the regulation of the net thermal impact on urban aquifers [22,25]. The results obtained indicated that the increase in flow rate implied a decrease in discharge temperature, and vice versa, which allowed regulating the transport and storage of heat in the subsurface (Fig. 10). The GWHP systems that generated the higher thermal impact when reducing their flow rate were operating in DM, due to their higher thermal power usage. However, these GWHP systems offer the advantage that, during heating periods, they must also increase their temperature change, but in negative values (Fig. 10). Therefore, despite significantly increasing their temperature in cooling mode, the annual thermal discharge is balanced by cooling the aquifer during heating mode periods. Another factor to consider is the amount of flow rate that must be increased to reduce discharge temperatures. As shown in Figs. 9 and 10, certain GWHP systems need to significantly increase flow rates to reduce temperature changes while maintaining the heating and cooling loads unchanged. The GWHP systems that had to implement the highest flow rates were those operating in DM (Fig. 10). Therefore, the associated cost of pumping a higher flow rate must also be considered. This method was based on the maximum values provided by the historical data of the pumps, offering real data on their maximum performance. However, this optimization allows setting the limit at a value of particular interest to the user, due to potential economic savings.

Depending on the characteristics of the aquifer and the position of the GWHP system with respect to the hydraulic gradient, both optimization alternatives should be tested to assess which one is more adequate to increase the aquifer's water availability and avoid compromising the operation of nearby GWHPs. On the one hand, increasing the flow rate would increase the area of thermal influence, but reduce the high temperature discharge temperatures (Figs. 9 and 10). Moreover, increasing discharge temperatures would raise the aquifer temperature, but also

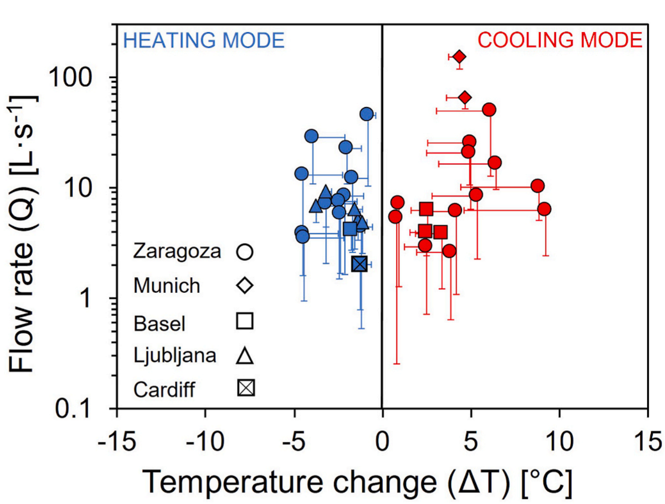

Fig. 9. Evaluation of the mean potential for optimization between Q and ΔT. Only the GWHP of Zaragoza operated in dual mode.

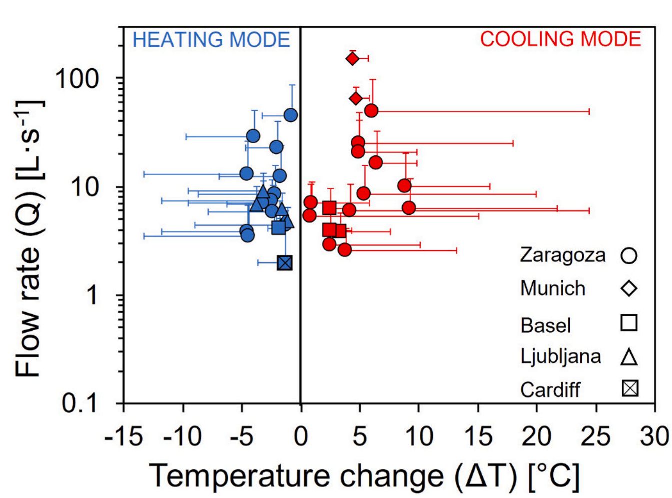

Fig. 10. Necessary increase of Q and ΔT in the optimization strategy. Only the GWHP of Zaragoza was operating in dual mode.

decrease the area of thermal influence by lowering the exploitation flow rates [50,51]. For instance, in GWHP systems located in close proximity, reducing discharge temperatures is advantageous. Conversely, in GWHP systems that are farther apart, reducing flow rates can minimize the potential for thermal interference between them. Controlling the expansion of thermal plumes and minimizing the thermal interference is essential to avoid performance losses in the GWHPs (augmenting COP), thereby reducing CO_2 emissions and achieving significant economic savings.

The proposed optimization method has some limitations related to the amount and quality of the data required to estimate the maximum energy demand at each established time step. Moreover, the aquifer thermal management method involves uncertainty about the spatial distribution of the GWHPs. Future studies should apply the management method to numerical models that allow for comparison and correlation of the results with different hydrogeological models, helping to select the most suitable optimization option for each installation. It is also recommended to perform numerical modeling, considering climatic variabilities associated with climate change predictive models, and to evaluate the adaptation of the technique to different energy demand contexts influenced by climate change.

4. Conclusions

This study presents a novel methodology for optimizing the operating regimes of existing GWHP systems, aiming to avoid thermal interference and maximize the efficiency of shallow geothermal resource use at an urban scale. The methodology was applied to 24 GWHP systems in five European countries, with different climatic conditions, uses and energy demands. This study demonstrated that the methodology can be applied to any GWHP, regardless of its operation mode (cooling, heating, or dual mode).

The proposed optimization methodology offers two different management alternatives without compromising the energy demand: (1) Increasing the flow rate and reducing temperature changes resulted in an average reduction of 1.48 °C in the discharge temperature across all GWHP systems, and (2) increasing the temperature changes while reducing the flow rates led to a reduction of the flow rates of all GWHP systems to an average 8.09 L s^{-1}.

The results indicate that this method is particularly effective for regulating thermal discharges from GWHP systems where well relocation is not feasible due to spatial or economic constraints. For example, in GWHP systems located in close proximity, reducing discharge temperatures is advantageous. Conversely, in GWHP systems that farther apart, reducing flow rates can help minimize the potential for thermal interference between them.

The present study contributes to advancing knowledge on geothermal energy in urban aquifers by developing an effective tool to manage and optimize the efficiency and sustainability of GWHP operation within the framework of thermal interference between systems. It also highlights the importance of continuous monitoring and control of shallow geothermal systems as a foundation for the sustainable management of both water and associated renewable energy resources.

However, the proposed management approach adds an additional constraint for operators of shallow geothermal systems, and the potential loss of technical efficiency should be further discussed. Further research is needed to determine whether the proposed exploitation regimes are feasible in different hydrogeological settings or, at the very least, in the specific hydrogeological conditions of the studied cities. Increasing flow rates may not always feasible due to the low hydraulic permeability of the aquifer. In addition, hydraulic and thermal parameters should be explored in greater detail.

For future research, we suggest implementing the optimized exploitation alternatives calculated using the proposed approach in numerical models.

CRediT authorship contribution statement

Jorge Martínez-León: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miguel Ángel Marazuela:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Carlos Baquedano:** Visualization, Methodology, Investigation, Formal analysis, Data curation. **Eduardo Garrido Schneider:** Writing – review & editing, Data curation. **Samanta Gasco-Cavero:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Olga García Escayola:** Writing – review & editing, Investigation, Funding acquisition, Data curation, Conceptualization. **Mitja Janža:** Writing – review & editing, Validation, Supervision, Data curation. **David P. Boon:** Writing – review & editing, Data curation. **Kai Zosseder:** Writing – review & editing, Validation, Data curation. **Jannis Epting:** Writing – review & editing, Methodology, Data curation. **Martin Binder:** Data curation. **Alejandro García-Gil:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.122163.

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