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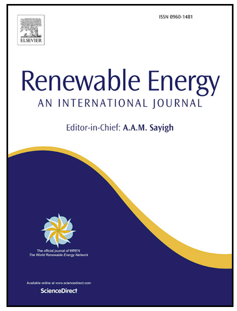

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THE T-I-G^{ER} METHOD: A GRAPHICAL ALTERNATIVE TO SUPPORT THE DESIGN AND MANAGEMENT OF SHALLOW GEOTHERMAL ENERGY EXPLOITATIONS AT THE METROPOLITAN SCALE[1]

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Abstract:

The number of shallow geothermal exploitations is growing without a widespread technical framework for this energy resource to be sustainably allocated between users. The thermal impacts that are produced by neighboring exploitations can deplete the resource if they are not properly distributed.

Therefore, we present an accessible and simple methodology to define the maximum potential that can be extracted and the position of the exploitations with the objective of limiting the thermal impacts to the available space.

The proposed method, named T-I-G^{ER}, takes into account the hydraulic and thermal properties of the subsurface as well as the size and orientation of the owner's plot. All this information is integrated in two different graphs: the thermal characteristic curve and the thermal plume graph. Therefore, the installer is able to graphically define the maximum potential and to check that thermal influences are restricted to the plot area.

We show with a hypothetical application in Azul city, Argentina, that the maximum extraction potential from similar plots can vary depending on the orientation of the plots with respect to groundwater flow. In the plots where the major dimension is parallel to groundwater flow, the maximum potential can be approximately twice the potential of the perpendicular plots.

Keywords: low-enthalpy geothermal energy, borehole heat exchanger, thermal characteristic curve, thermal contamination.

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[1] **Acronyms:**

SGE: Shallow Geothermal Energy — TCC: Thermal Characteristic Curve

SGP: Shallow Geothermal Potential — TPG: Thermal Plume Graph

BHE: Borehole Heat Exchanger

1 INTRODUCTION

As a consequence of the world-wide concern on climate change, national legislations have been modified to implement measures to sustainably meet energy needs [1], [2]. This results in an increase in private initiatives and investments on renewable energies, which are exponentially growing in an effort to reduce greenhouse gas emissions. Consequently, renewable energies have been experiencing a boom in recent years.

The advantages of shallow geothermal energy (SGE), such as its ubiquity and independence of weather conditions [3], compared to other renewable energies make SGE a feasible option to certain stakeholders. Despite its advantages, the success and spreading of this technology [4] are highly dependent on sociological and cultural aspects, as suggested by [5], partly due to economic factors. To promote the exploitation of SGE, the authorities in charge should ensure the long-term efficiency of these installations through sustainable resource management.

SGE is stored in the ground up to 400 m in depth. It is usually exploited with borehole heat exchangers (BHE) coupled with heat pumps, among other configurations [6]. A liquid, which can have enhanced thermal properties or simply be water, is recirculated inside the BHE where the energy is extracted from or dissipated in the ground and transferred to the heat pump.

Although SGE is a renewable energy, it is a limited energy resource that can be overexploited [7]. The efficiency and sustainability of BHEs rely on both the BHE being produced and any neighboring BHE [8].

On the one hand, sizing of the BHEs based on the geological, hydrogeological and geothermal properties of the subsurface is required to produce the suitable potential, according to the thermal restoration capacity of the subsurface. This would ensure efficiency during the producible life of the proposed BHE [9].

On the other hand, nearby exploitations can affect the optimal performance of the BHE through their thermal plumes [10]. A thermal plume is the thermal contamination that occurs in the subsurface due to the extraction or dissipation of heat with the BHEs. The size and intensity of thermal plumes depend on different variables, such as the extracted shallow geothermal potential (SGP), the groundwater velocity and other thermal parameters (i.e., thermal conductivity, heat capacity and thermal dispersion). These thermal plumes are ultimately responsible for depleting SGE resources and should be controlled.

Moreover, the subsurface exploitation of SGE conflicts with other subsurface resources. Currently, the first steps towards the holistic management of the urban subsurface are beginning to be defined [11]–[13]. Nevertheless, the instruments to implement these steps, especially those related to SGE management, are not sufficiently developed nor applied.

The lack of applied management methodologies that consider the above-mentioned aspects is leading to thermal interferences between exploitations [14] and, consequently, to efficiency losses. The administration responsible for SGE management only defines maximum distance thresholds between SGE exploitations [15]. At most, more advanced geological and hydrogeological studies are required by administrators when the potential production exceeds a limit. However, this is not the case for individual BHEs [16]. The BHE installer is responsible for ensuring the long-term efficiency of the exploitations, which implies that BHE sizing for the exploitation should take into account its relationship with neighboring exploitations. One of the advantages of SGE production, its null visual impact, becomes a disadvantage if no records for current SGE exploitations are available. Therefore, a level of uncertainty must be assumed when sizing new BHEs due to the uncertainty of the thermal environment in the subsurface.

Existing SGE management methodologies are based on numerical modeling. They require a comprehensive understanding of the thermal system over the entire city. These models must represent the complex thermal relationships between all of the subsurface entities, which represent heat sources or sinks, such as existing BHEs or wastewater network pipes [17]. These tools cannot be extensively used due to two main problems: the complexity during definition of conceptual geothermal models and the scarcity of highly qualified staff to construct, maintain and operate such numerical models. These disadvantages make it difficult to widely implement numerical models, so they are relegated to mature SGE markets where adequate information for the thermal state of the subsurface and exploitation data are available [18]–[20]. In contrast, for young SGE markets with incipient exploitation development, more accessible and simple methodologies are required to manage SGE production.

Among these alternative methodologies, those based on the quantification of SGP are highly developed. Usually, geographical information systems (GIS) technology is typically applied to create maps with SGP distribution [21]–[25] and an initial estimate of thermal influence [26]. Progressively, GIS methodologies have started to reduce the scale of work and take into account additional variables such as urban planning and population density [27], [28].

However, there is still a need to provide more accessible tools and methodologies to installers who are in charge of designing SGE exploitations. Their responsibility to guarantee a long efficiency life should be supported by reliable and accessible tools that account for the geological, hydrogeological and geothermal subsurface properties and include the uncertainties of the thermal behavior of groundwater. Existing commercial and non-commercial tools support the definition of BHEs' properties (such as its length) based on the subsurface thermal properties [29] and the BHE performance [30], without considering the thermal impacts on the aquifer. To overcome this gap, this study presents a methodology based on a graphical solution named the T-I-G^{ER} (Thermal Impacts Graph^{ER}) method. It is based on two different graphs that represent the thermal contamination in the subsurface: the thermal characteristic curve (TCC) and the thermal plume graph (TPG). These graphs can be easily created and applied by the BHE installers.

The structure of the paper is as follows. In Section 2 the T-I-G^{ER} method is introduced, describing the main concepts and inputs required. In Section 3, a hypothetical example of the proposed methodology is presented for the city of Azul, Argentina, whose climate, subsurface and urban characteristics could make it a case study in Argentina for SGE production. Finally, conclusions are included in Section 4.

2 T-I-G^{ER} METHOD

In this section, the mathematical basis of the T-I-G^{ER} is method is presented, along with the definition of its two innovative graphs and a description of the information required for implementing this method.

2.1 Underlying theory

The thermal behavior can be simulated with the heat transport equation in porous media [31]:

$$\rho c\frac{\partial T}{\partial t} + q\rho_w c_w\frac{\partial T}{\partial x} - \lambda_x\frac{\partial^2 T}{\partial x^2} - \lambda_y\frac{\partial^2 T}{\partial y^2} - S = 0 \quad (1)$$

where T is the temperature as the state variable (*K*), q is the groundwater velocity, also known as Darcy velocity (*m/s*), ρc and $\rho_w c_w$ are the volumetric heat capacity of the subsurface and water ($J/m^3/K$), respectively, $\lambda_{x/y}$ is the effective thermal conductivity in the longitudinal and transverse directions (*W/m/K*), *x/y* are the Cartesian coordinates, *t* is the time (*s*) and *S* is the heat source/sink term (W/m^3).

Eq. (1) has been solved under different boundary conditions [32]. [33] proposed the following analytical solution for this differential equation in the transient state:

$$\Delta T(x,y,t) = \frac{q_L}{4\,\pi\sqrt{\lambda_x\lambda_y}}exp\left[\frac{\rho_w c_w q}{2\lambda_x}x\right]\int_0^{\frac{(\rho_w c_w)^2 t}{4\,\rho c\lambda_x}} exp\left[-\phi - \left(\frac{x^2}{\lambda_x}+\frac{y^2}{\lambda_y}\right)\frac{(\rho_w c_w q)^2}{16\,\lambda_x\phi}\right]\frac{d\phi}{\phi} \quad (2)$$

where ϕ is the integration variable, ΔT is the temperature change produced in the ground (*K*) and q_L is the heating rate or SGP (*W/m*). This last variable is the gross SGP extracted from the subsurface, without considering the loss of energy during SGE production.

Eq. (2) is based on the moving infinite line source model (MILS) and takes into account the thermal dispersion heat transport mechanism. It includes the presence of groundwater flow through the advection and dispersion heat transport mechanisms. This solution applies for an infinite, homogeneous and isotropic domain in a uniform groundwater velocity field where a heat source/sink is conceptualized as an infinite line.

The MILS has been previously applied by [26], [34]–[36] to represent the thermal behaviour of groundwater under the influence of the BHE. Moreover, it has been validated for the standard variable range of geological properties in [26].

2.2 T-I-G^{ER} graphs

The following two graphs represent the characteristics of the thermal plumes produced by the BHE. They both support the decision making process when defining and managing SGE exploitations; the optimal SGP and the position of the BHE can be established based on the thermal impacts on the subsurface. Additional information must be considered based on the specific characteristics of the site when exploiting

SGE, to avoid undesirable consequences [37], [38]. Such specifications are not considered by the T-I-G^{ER} method.

2.2.1 The Thermal Characteristic Curve (TCC)

The T-I-G^{ER} method is based on the thermal characteristic curve (TCC), which was previously introduced in [28]. The TCC graphically represents the thermal behavior of the subsurface media when SGE is being exploited by a BHE. It is an SGP vs. thermal plume size (length x and width y) graph, i.e., the TCC represents $q_L$vs x, y. A synthetic TCC is shown in **Figure 1**.

Eq. (2) can be reformulated to obtain an expression in the form of $q_L = f(x)$, Eq. (3), to represent the thermal plume length. The thermal plume width is represented with an expression in the form of $q_L = f(y)$, Eq. (4). Both expressions are implemented to create the TCC. These expressions are formed by setting the opposite coordinate to zero:

$$q_L = f(x, y = 0) = \frac{\Delta T 4\pi\sqrt{\lambda_x \lambda_y}}{exp\left(\frac{q\rho_W c_W}{2\lambda_x}x\right)\int_0^{\frac{(\rho_W c_W)^2 t}{4\,\rho c\lambda_x}} \frac{1}{\varphi} exp\left(-\varphi - \left(\frac{x^2}{\lambda_x}\right)\frac{(q\rho_W c_W)^2}{16\lambda_x \varphi}\right) d\varphi} \quad (3)$$

$$q_L = f(x = 0, y) = \frac{\Delta T 4\pi\sqrt{\lambda_x \lambda_y}}{\int_0^{\frac{(\rho_W c_W)^2 t}{4\,\rho c\lambda_x}} \frac{1}{\varphi} exp\left(-\varphi - \left(\frac{y^2}{\lambda_y}\right)\frac{(q\rho_W c_W)^2}{16\lambda_x \varphi}\right) d\varphi} \quad (4)$$

The TCC can be used for two different approaches. First, if the available area inside the plot is known, the optimal SGP can be determined by the TCC. Conversely, assuming that the SGE production is known, the TCC determines the size of the thermal plume produced by the BHE.

Additionally, the TCC offers information related to the maximum SGP that can be extracted without increasing the temperature more than 10 K at the BHE wall (**Figure 1**).

2.2.2 The Thermal Plume Graph (TPG)

To determine the shape of thermal plumes when defining the BHE position, a second graph is presented to complement the TCC. It contains the length and width of the thermal plume, the position of the maximum width and the upstream and downstream distance from the BHE (**Figure 2**).

The TPC is drawn from Eq. (2). The isothermal line can be determined by the inversion of $\Delta T = f(x, y)$. This expression represents the set of points (x, y) that defines the thermal plume. The inversion is performed numerically to state y as a function of x.

With the TPG, the installer is able to locate the BHE inside the cadastral plot to maintain the thermal contamination inside the plot. This graph depends on the hydraulic and thermal properties of the cadastral plot (like the TCC) but also depends on the SGP that would be produced with the BHE. Therefore, each BHE inside a cadastral plot will need a different TPG.

2.3 Required information

The T-I-G^{ER} method includes two different working scales: on the larger metropolitan scale, the local authorities should define regulation parameters to restrict the SGE exploitation (named constraining variables) and should accomplish the elementary studies for the geological and hydrogeological properties of the city to provide the initial data; on the smaller plot scale, the installer is responsible for sizing the SGE exploitation. For each scale, the responsible agents and the temporal scales are different, i.e., they have different participation frequencies. While the local administration only has to participate, e.g., once every five years to generate and update the regional information, the installers participate at every SGE site.

The first step in the proposed methodology is performed by the local administration, which must provide the required data at the metropolitan scale. These data are predominantly standard and are typically available due to previous studies related to groundwater management, so it is not necessary to generate new data specifically for SGE management.

Once the regional data has been provided by the local administration, the installer has to consider the specific characteristics of the cadastral plot to ensure the efficiency and high performance of the SGE exploitation. The working scale in this step is reduced. The installer must focus on the site-specific cadastral plot.

2.3.1 Hydraulic and geothermal characterization of the subsurface

Groundwater presence is a determinant factor in the efficiency and the recovery of SGE exploitations [36], [39]; therefore, a hydrogeological study must be performed. Moreover, the piezometric surface and the hydraulic conductivity are common outputs from a general hydrogeological study. This information can be used to generate the groundwater velocity field of the exploited aquifer by applying Darcy's Law:

$$q = K \cdot i \qquad (5)$$

where q is the Darcy velocity or groundwater velocity (*m/s*), K is the hydraulic conductivity (*m/s*) and *i* is the hydraulic gradient. The slope of the piezometric surface can be calculated using inherent GIS tools to determine the hydraulic gradient field.

The direction of groundwater velocity will also be of interest to constrain the thermal contamination to the available space. The groundwater flow net indicates this aspect and can also be defined from the piezometric surface. The equipotential (i.e., piezometric lines) and flow lines describing the groundwater flow net can be created using standard GIS tools.

Ideally, geothermal variables (i.e., thermal conductivity, volumetric heat capacity and thermal dispersion) should be obtained from field studies. However, they can be obtained from the literature without introducing too much error on the estimation if groundwater is present due to the small range of variation of geothermal variables compared with the variable range of groundwater velocity [40]. Groundwater velocity varies by several orders of magnitude (e.g., from 10^{-5} m/s to 10^{-8} m/s for sedimentary aquifers), so it has much more relevance than geothermal parameters on the final estimation of SGP and thermal impacts.

2.3.2 Constraining variables

To create the TCC, additional information must be defined by the administrator: the constraining variables ΔT and *t*. The uncertainties about the geological, hydrogeological and geothermal models can be considered by adjusting the values of both constraining variables. More conservative values of these variables should be assumed if no reliable studies are available.

The temperature change, ΔT, represents the threshold upon which local administration will consider that thermal contamination is produced. The more reliable the conceptual model describing the thermal behavior of the subsurface is, the higher is the ΔT value. The thermal plume encloses an area where the BHE produces a temperature change greater than ΔT.

The constraining variable *t* represents the elapsed time since the start of the BHE operation. It depends on how long the BHE is working in the cooling or heating mode. The longer period should be selected.

When creating the TCC, it is required that both constraining variables, ΔT and *t*, are established by the local administration. Thus, the administration can regulate the density of SGE exploitations according to the existing geological and hydrogeological knowledge of the area.

2.3.3 Urban planning and limiting plot dimensions

To avoid thermal interferences between exploitations, the thermal plume must be contained inside the available surface, i.e., the owner's cadastral plot. The cadastral plot distribution is usually provided by local authorities, and it is usually available online through web map services.

Next, the installer must first determine the feasible areas inside the cadastral plot to drill the BHE. The installer must consider the existence of underground infrastructures and facilities, such as electricity or water supply network pipes, and the accessibility of the borehole drilling rig.

When the feasible areas for drilling have been demarcated, the installer has to overlap these areas with the groundwater flow nets. The installer defines the maximum dimensions (length and width) available inside the cadastral plot according to the groundwater flow net. The maximum length and width should be parallel and perpendicular to groundwater flow lines, respectively, to obtain higher SGP values. The orientation of the cadastral plot dimensions must concur with the groundwater flow lines to optimize the SGE exploitation (**Figure 3**). These dimensions limit the size of the thermal plume and, hence, the SGP that can be exploited.

The maximum length, denoted as *L*, defines the maximum extent of the thermal plume produced by a BHE. It includes both the distances downstream and upstream of the BHE. The maximum width, denoted as *W*, establishes the maximum breadth of the thermal plume at both sides of the longitudinal thermal plume axis. These dimensions, *L* and *W*, will characterize the cadastral plot and can be obtained with standard GIS tools. They support the definition of the maximum SGP that can be extracted in a sustainable manner based on the thermal characteristic curve (TCC). In a cadastral plot whose larger dimension is parallel to groundwater flow, such as Plot A shown in **Figure 3**, the SGP would be greater than in a cadastral plot perpendicular to groundwater flow (Plot B in **Figure 3**).

3 APPLICATION

3.1 General settings

The city of Azul is located in the middle of the Buenos Aires province, in the La Pampa region (**Figure 4**). It is characterized by a humid subtropical climate, with an average precipitation of 960 mm/y and an annual average temperature of 14ºC. Azul city is located in the Del Azul Creek basin, from which it is named. The regional geological and hydrogeological properties are described in [41].

Drinking water is produced in the town from groundwater resources, so the subsurface system is well studied and controlled in this area. Several geological and hydrogeological analyses had been conducted for the study area at a local scale [42], [43]. However, they are mostly related to the hydraulic behavior, while the thermal properties have not been studied.

The main hydrogeological unit is the Pampeano aquifer, which encompasses both Postpampeano and Pampeano sediments (Pleistocene-Holocene age). They are composed of silts, sandy silts and clayey silts. Underlying these sediments is the Precambrian basement, between 111 and 143 m depth.

Especially relevant in this area is the generalized problem of high levels of arsenic in the groundwater [44], [45]. As suggested by [46], the SGE exploitation could induce arsenic mobility. As a result, public administration should control the chemical and physical properties of groundwater during exploitation of SGE to ensure safety, especially if the exploited aquifer is used for the production of drinking water, as is the case for Azul city.

3.2 Input data

3.2.1 Geothermal parameters

The thermal properties obtained from existing studies and literature [40] are shown in **Table 1**.

Table 1. Hydraulic and thermal properties considered for the underground media in Azul city.

Parameter	Value	Unit
Thermal conductivity	2.7	**W/m/K**
Volumetric Heat Capacity	$2.8 \cdot 10^{6}$	**J/m^3/K**
Thermal dispersion	10/1	**m**

3.2.2 Groundwater velocity and flowlines

The hydraulic conductivity of the main aquifer in Azul city is $5.8 \cdot 10^{-5}$ m/s. **Figure 5** shows the piezometric surface in the area and the groundwater velocity field derived from it according to Eq. (5). These hydraulic properties were obtained from [43].

3.2.3 Constraining variables

In the case of Azul city, intermediate conservative values of ΔT and t can be assumed due to the reliable knowledge of the geology and hydrogeology. The performance of the in situ thermal tests to estimate thermal dispersion would lead to more flexible values of both constraining variables. Their values are shown in **Table 2**. The lower the ΔT value, the bigger the thermal plumes, so the number of BHEs allowed would be reduced. The influence of the elapsed time depends on the temporal evolution of the system: the longer the t value, the bigger the thermal plumes, until the steady state is reached, when the thermal plume would not grow larger.

Table 2. Constraining variables values that are required to construct the TCC.

Constraining Variable	Value	Unit
Temperature increment, ΔT	0.5	**K**
Elapsed time, t (6 months)	15552000	**s**

3.2.4 Urban planning and limiting plot dimensions

The Azulean population is over 60.000 inhabitants, and its urbanization is primarily horizontal, with single-family attached homes. The blocks of Azul city are shown in **Figure 5**. The blocks are usually square, with sides of 100 m long, and divided into 20 cadastral plots on average with irregular distributions [47].

In this work, the possibilities of SGE exploitation were analyzed for urban block 186 shown in **Figure 6**. The proposed block is divided into 22 cadastral plots. The optimal plots for SGE exploitations are those oriented in the direction of groundwater flow. In this work, two plots with similar areas and different orientations will be analyzed in order to evaluate the consequences of the groundwater flow direction. The limiting dimensions for each cadastral plot are shown in **Figure 6**.

3.3 RESULTS

At this stage, the TCC must be available with the objective to define the SGP and the position of each BHE. Ideally, the public administration should provide the TCC and the shape of the thermal plume through an online web map application. If this is not the case, the installer could create them with the Python scripts available as supplementary material.

3.3.1 Shallow geothermal potential (SGP)

At this point, the TCC can answer two questions: if the energy demand that must be satisfied with SGE is known, the suitability of SGE exploitation can be defined. The TCC indicates the length and width of the thermal plume; if these dimensions can be accommodated inside the cadastral plot, then the SGE exploitation would be feasible. The maximum SGP that can be exploited can also be obtained from the TCC. The TCC returns a value of SGP for dimension L and a different value for dimension W. The smaller of the two values indicates the potential that can be exploited.

Cadastral plots 15 and 5 share the hydraulic and thermal properties that define the TCC. In this situation, the same TCC can be used for both plots which is shown in **Figure 7**. The TCC indicates that the maximum SGE potential for one BHE is 89 W/m. However, the thermal plume size produced by this maximum SGP (L = 23 m and W = 14 m) is greater than the available space in both cadastral plots; therefore, it is necessary to define smaller SGP values for both plots.

The limiting dimension of cadastral plot 15 is W = 10 m. According to the TCC, the SGP that can be extracted from one BHE in this plot is 40 W/m. For cadastral plot 5, the SGE potential that can be extracted is 21 W/m, corresponding to L = 10 m, which is the limiting dimension of this plot (**Figure 7**).

3.3.2 Allocation of BHEs according to thermal contamination

Each BHE defined previously with different SGPs has its own TPG. Therefore, two TPGs are created to support the allocation of the BHEs. They are shown in **Figure 8**.

The thermal contamination can be manually drawn from the TPG as shown in **Figure 9**. The characteristics of cadastral plot 15 would allow two BHEs inside the available space. For standard BHEs of 115 m depth, the total SGP that could be extracted from cadastral plot 15 would be 2 x 115 (m) x 40 (W/m) = 9.2 kW.

The orientation of cadastral plot 5 with respect to groundwater flow direction is not efficient to extract SGE. This implies that a very low SGP could be extracted without thermally affecting the neighboring plot (21 W/m). To obtain approximately the same SGP from this plot, four BHEs would be required: 4 x 115 (m) x 21 (W/m) = 9.6 kW.

Other configurations are possible by varying the number of boreholes and the limiting dimensions, but in this work, the standard criterion is to adjust the number of BHEs. The installer could try different configurations of the BHE length and number to obtain the required SGP.

3.3.3 Comparison with a reference scenario

To compare the determined results, an alternative scenario is proposed to use as a reference. Recommendations of existing Spanish regulations are considered, as there are no applicable regulations related to SGE in Argentina. Following its criteria for SGE exploitations under 30 kW, the BHE should be located at a minimum distance of 3 m from the plot boundaries and separated by at least 6 m.

According to this schema, 4 BHEs can be suitable for each plot. These minimum distances are independent of the extracted SGP, so the maximum SGP of 30 kW is assumed to be extracted. This implies that every BHE should extract 30 (kW) / 4 = 7.5 kW. For BHEs at 115 m depth, the SGP per unit length would be 7.5 (kW) / 115 (m) = 65.22 W/m.

Figure 10 shows the thermal plumes produced by these BHEs and the expected thermal interferences. As a consequence of the orientation between the groundwater flow and the cadastral plots, the thermal plumes in plot 15 are aligned; this would reduce BHE efficiency.

These thermal plumes represent the thermal contamination with temperature values above 0.5K. By applying the superposition principle, the temperature inside the green areas would be increased by more than 1 K. In cadastral plot 5, the inner thermal influences among BHEs could be neglected. However, the thermal plumes in this plot encroach on the neighboring plots, depleting their energy resource. As a consequence of these thermal interferences, the expected SGE potential of 7.5 kW could not be efficiently extracted from any of these cadastral plots.

4 CONCLUSIONS

The T-I-G^{ER} methodology allows installers to allocate SGE resources in a fair and sustainable manner by taking into account the thermal impacts produced in the subsurface, specifically in groundwater. It integrates the participation of public administration in charge of the SGE management and private installers of SGE exploitations. The steps can be performed with accessible tools: some steps use standard hydrogeological studies and those steps specifically related to SGE use the tools that are provided in this work.

As the application in Azul city has shown, the shape and orientation of the cadastral plot is highly relevant when sizing SGE exploitations, especially when groundwater flow exists. If these inputs are not considered, the thermal impacts could affect neighboring BHEs, exceed the plot boundaries and reduce the SGE potential of adjacent plots depleting the energy resource.

Ideally, access to required data (groundwater net flow, cadastral data, thermal characteristic curves and thermal plume graphs) should be available through a web map application. The installer would not need advanced knowledge on specific techniques, such as numerical modeling, to ensure the sustainability of SGE resources.

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Figure 1. Sketch of synthetic Thermal Characteristic Curve (TCC). The TCC represents the relation between the SGP and the length of its thermal impacts in the subsurface.

Figure 2. Sketch of the synthetic thermal plume graph (TPG). The TPG represents the size and dimensions of the thermal impacts for a particular BHE in a plot.

Figure 3. Length (*L*) and width (*W*) dimensions of cadastral plots with respect to groundwater flow.

Figure 4. Location map of Azul city in Pampean plains.

Figure 5. Regional piezometry, groundwater flow net and Darcy velocity in Azul city.

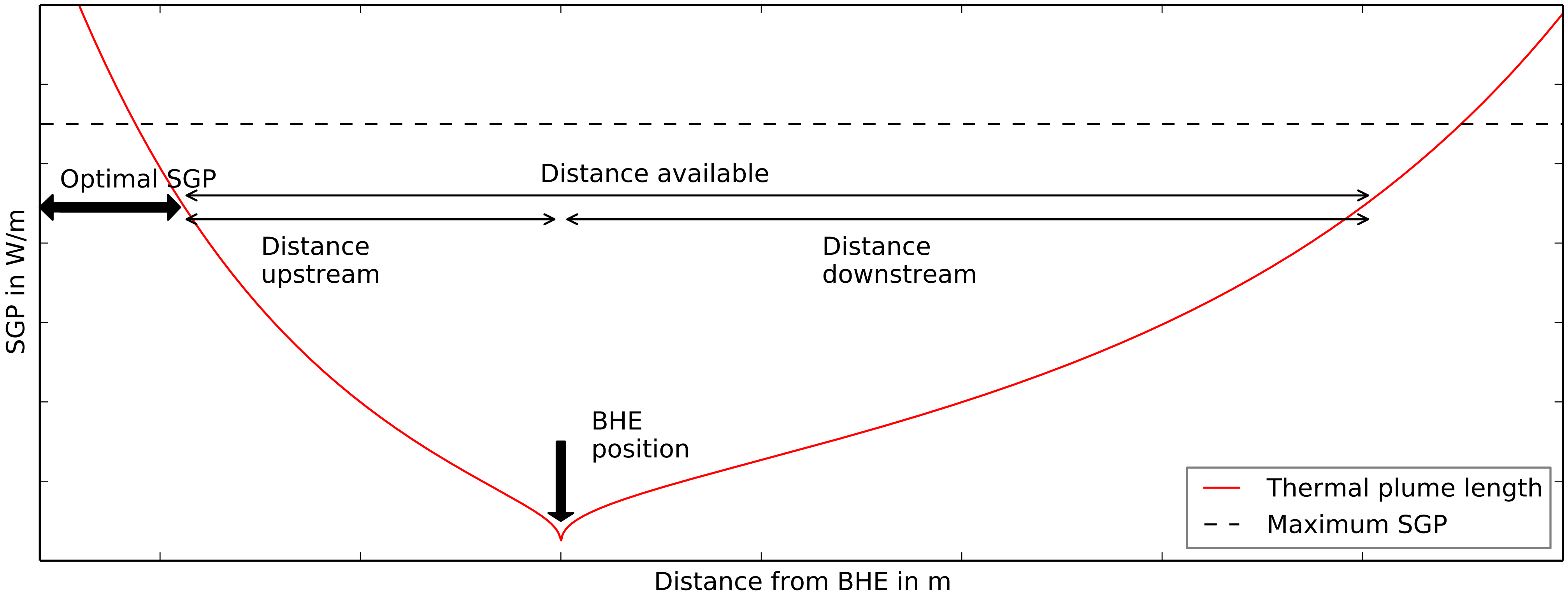
Figure 6. Location of the block and the cadastral plots under study. The dimensions *W* and *L* that are required to size SGE exploitation are remarked for cadastral plots 5 and 15. These dimensions are defined according to the groundwater flow direction.

Figure 7. Thermal characteristic curve for cadastral plots 15 and 5. The limiting dimensions for each plot are represented along with the corresponding SGP.

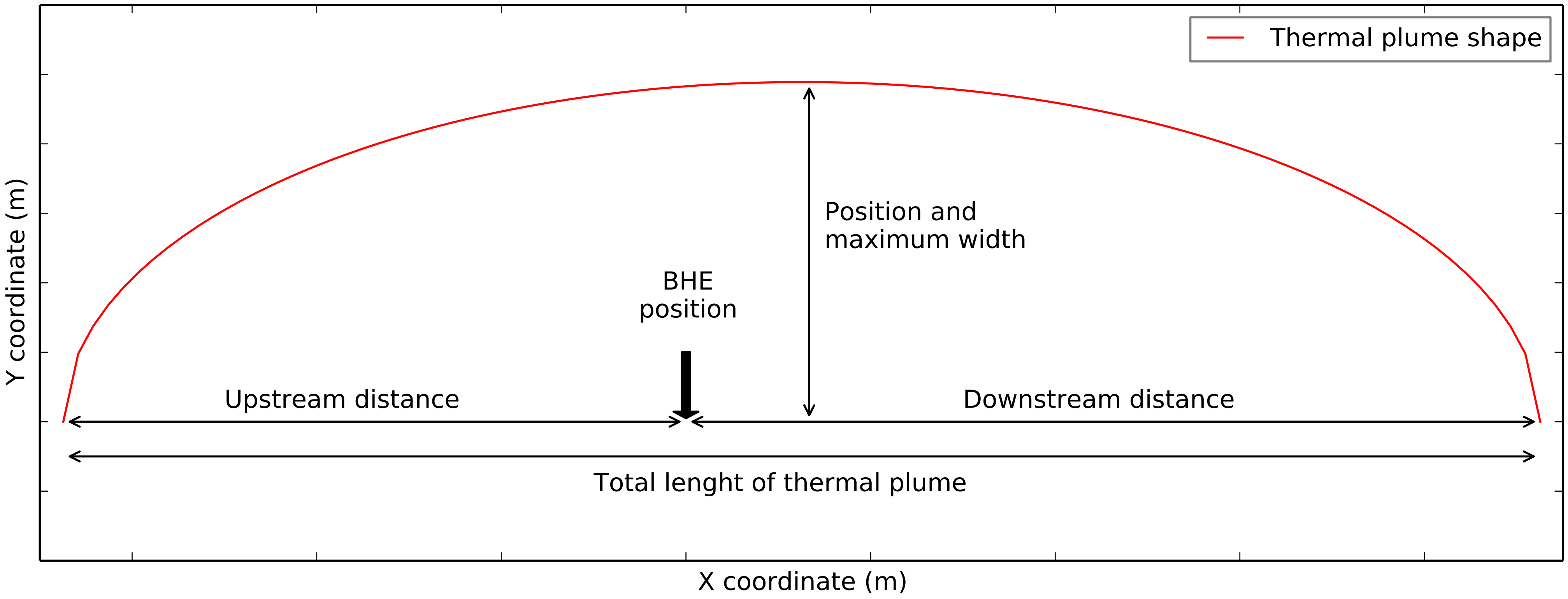
Figure 8. Thermal plume graphs for the SGE exploitations in cadastral plots 15 and 5. This graph complements the TCC when drawing the thermal plume.

Figure 9. Configuration of the BHE exploitations in cadastral plots 15 and 5. To extract a similar SGP from these different plots, the less favourable plot (cadastral plot 5) requires more BHEs.

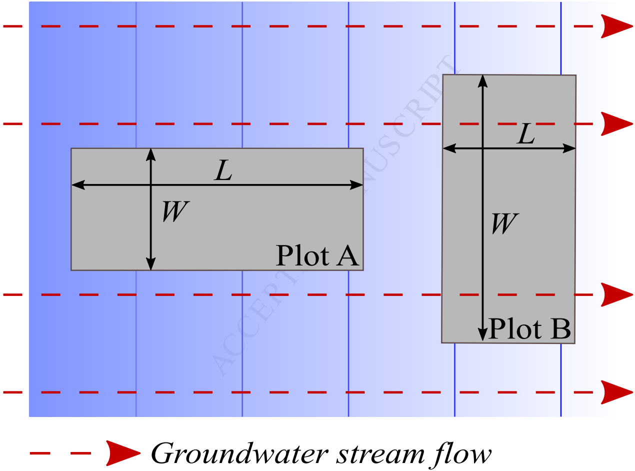
Figure 10. Thermal affections that would be produced following the existing regulations in the reference scenario. These thermal plumes can deplete SGE of the plot with inner thermal influences and the neighbouring plots with outer thermal influences.



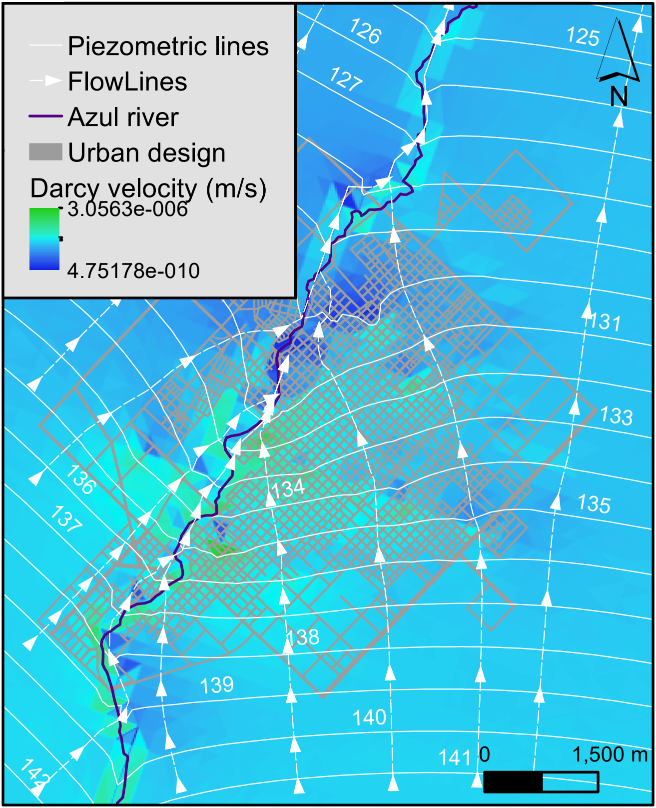
Optimal SGP
Distance available
Distance upstream
Distance downstream
BHE position
Thermal plume length
Maximum SGP
SGP in W/m
Distance from BHE in m

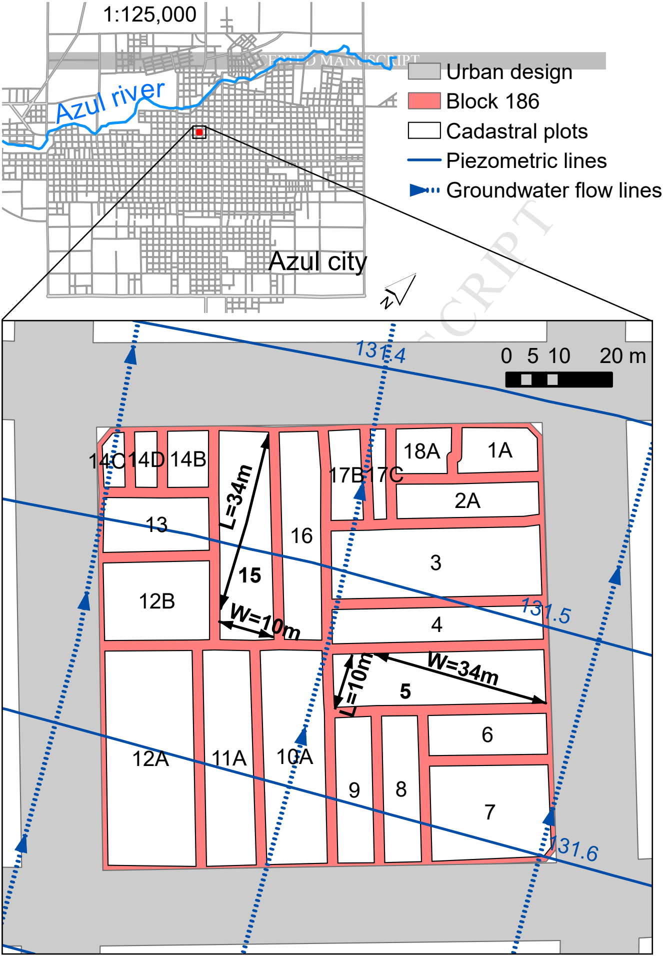


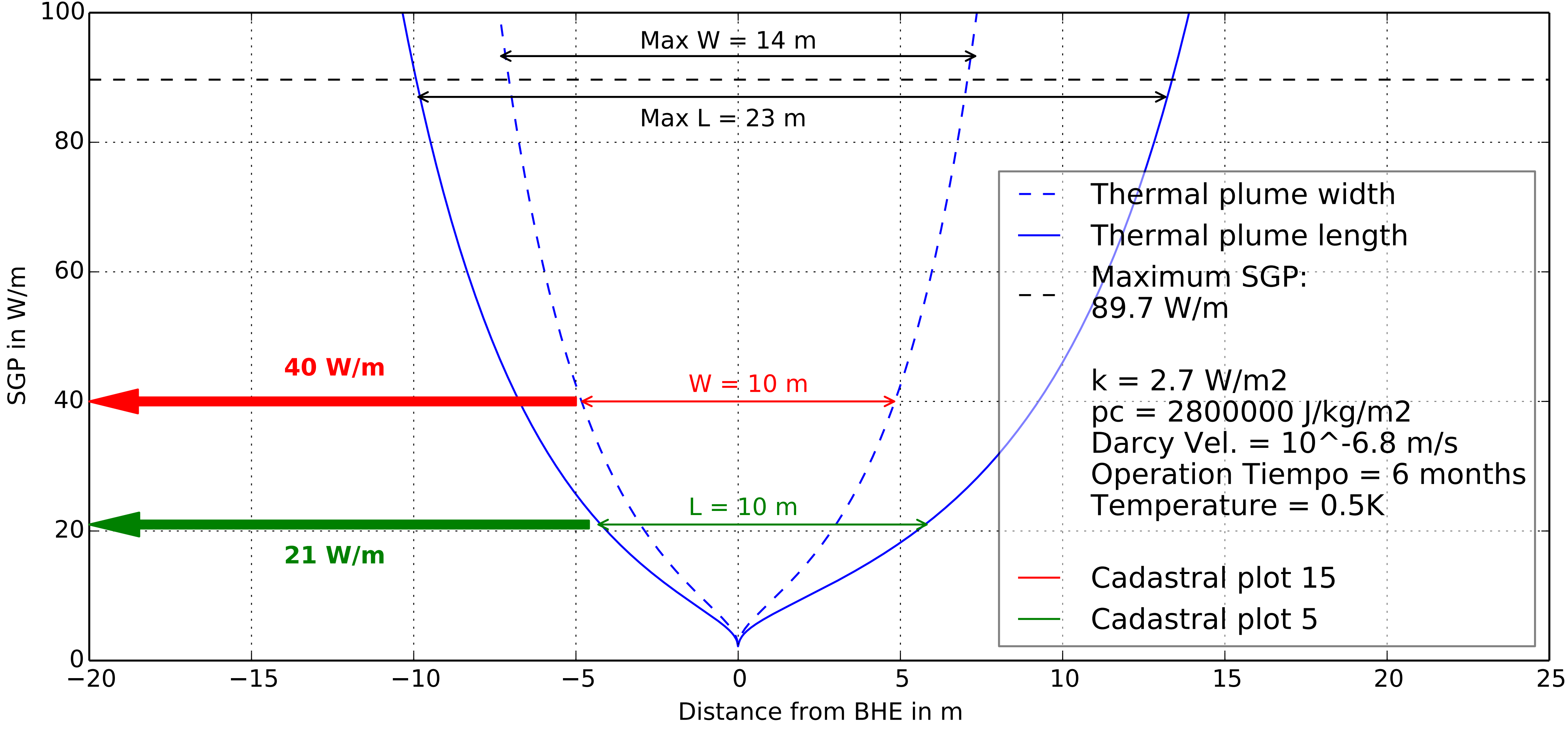
Thermal plume shape
Position and
maximum width
BHE
position
Upstream distance
Downstream distance
Total lenght of thermal plume
Y coordinate (m)
X coordinate (m)


L
W
Plot A
L
W
Plot B
Groundwater stream flow

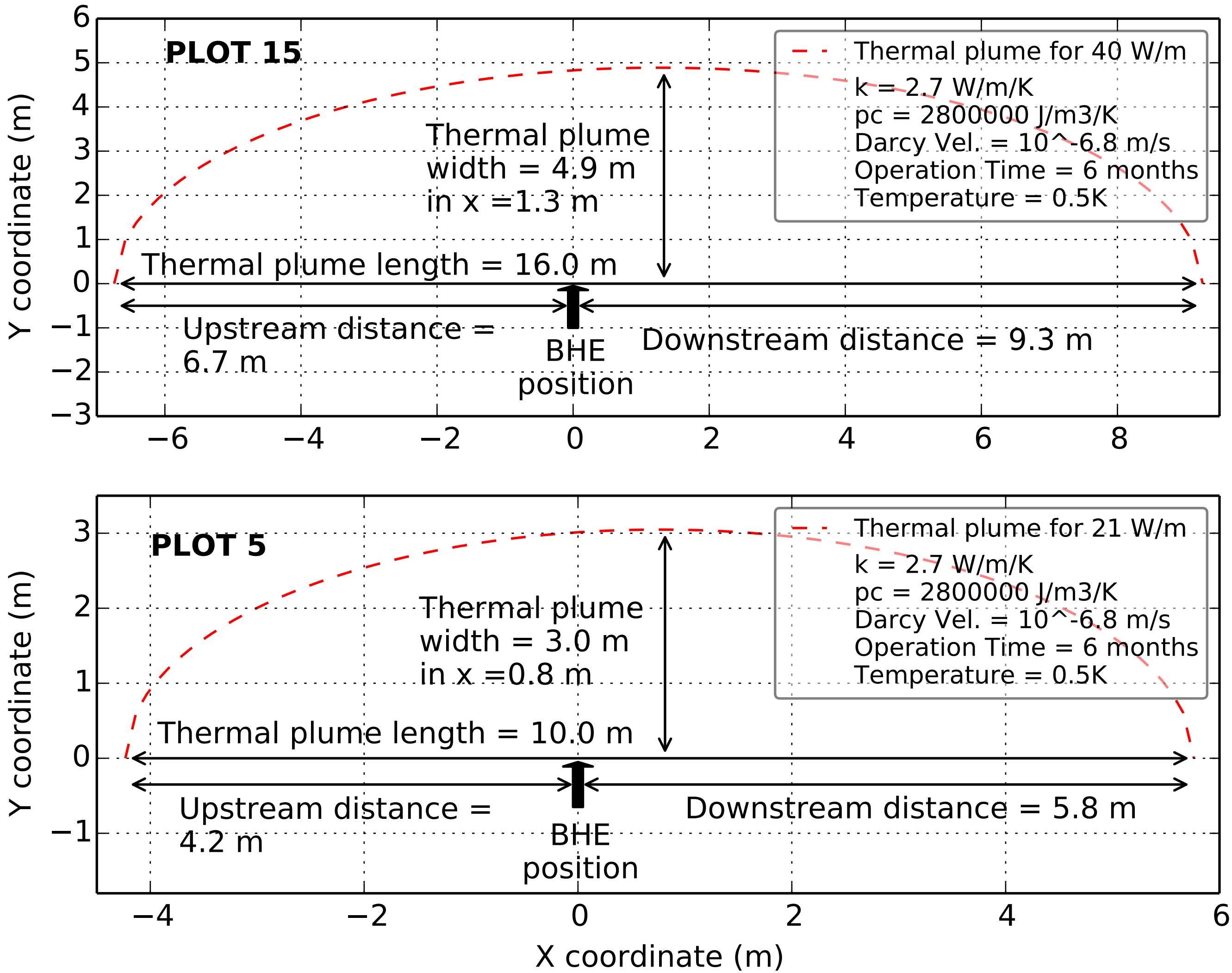

PARAGUAY
Pacific Ocean
BRAZIL
ARGENTINA
URUGUAY
Buenos Aires
Province
AZUL
36º47' S
CHILE
59º51' W
Atlantic Ocean

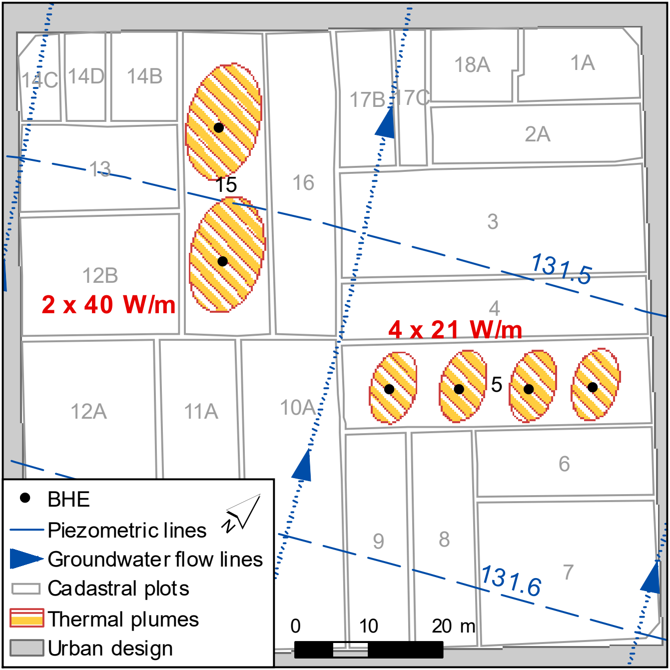

Piezometric lines
FlowLines
Azul river
Urban design
Darcy velocity (m/s)
3.0563e-006
4.75178e-010
N
125
126
127
131
133
134
135
136
137
138
139
140
141
142
0
1,500 m

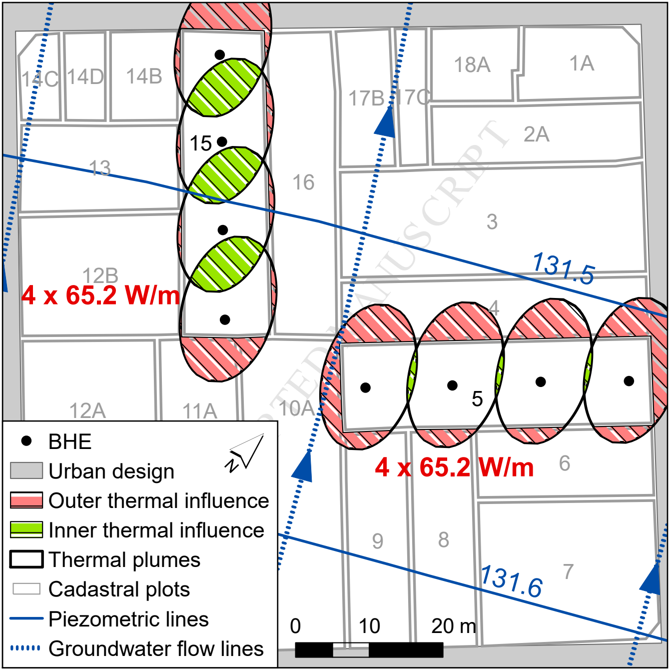

1:125,000
Urban design
Block 186
Cadastral plots
Piezometric lines
Groundwater flow lines
Azul river
Azul city
N
0 5 10 20 m
131.4
131.5
131.6
14C
14D
14B
15
16
17B
17C
18A
1A
2A
13
3
12B
4
L=34m
W=10m
W=34m
L=10m
5
12A
11A
10A
9
8
6
7



Max W = 14 m
Max L = 23 m
40 W/m
W = 10 m
L = 10 m
21 W/m
Thermal plume width
Thermal plume length
Maximum SGP:
89.7 W/m
k = 2.7 W/m2
pc = 2800000 J/kg/m2
Darcy Vel. = 10^-6.8 m/s
Operation Tiempo = 6 months
Temperature = 0.5K
Cadastral plot 15
Cadastral plot 5
SGP in W/m
Distance from BHE in m
100
80
60
40
20
0
−20
−15
−10
−5
0
5
10
15
20
25


PLOT 15
Thermal plume for 40 W/m
k = 2.7 W/m/K
pc = 2800000 J/m3/K
Darcy Vel. = 10^-6.8 m/s
Operation Time = 6 months
Temperature = 0.5K
Thermal plume width = 4.9 m in x =1.3 m
Thermal plume length = 16.0 m
Upstream distance = 6.7 m
BHE position
Downstream distance = 9.3 m
PLOT 5
Thermal plume for 21 W/m
k = 2.7 W/m/K
pc = 2800000 J/m3/K
Darcy Vel. = 10^-6.8 m/s
Operation Time = 6 months
Temperature = 0.5K
Thermal plume width = 3.0 m in x =0.8 m
Thermal plume length = 10.0 m
Upstream distance = 4.2 m
BHE position
Downstream distance = 5.8 m
Y coordinate (m)
X coordinate (m)


14C
14D
14B
18A
1A
17B
17C
2A
13
15
16
3
131.5
12B
2 x 40 W/m
4
4 x 21 W/m
5
12A
11A
10A
6
BHE
Piezometric lines
Groundwater flow lines
Cadastral plots
Thermal plumes
Urban design
N
9
8
7
131.6
0
10
20 m


14C
14D
14B
15
13
16
17B
17C
18A
1A
2A
3
12B
4 x 65.2 W/m
4
131.5
12A
11A
10A
5
6
4 x 65.2 W/m
9
8
7
131.6
BHE
Urban design
Outer thermal influence
Inner thermal influence
Thermal plumes
Cadastral plots
Piezometric lines
Groundwater flow lines
N
0
10
20 m

Highlights:

- A simple method is proposed to sustainably size shallow geothermal exploitations
- A graph relates the maximum shallow geothermal potential and its thermal impacts
- It is based on local thermal and groundwater properties and on the plot orientation

c	Specific heat capacity (J/kg/K)
i	hydraulic gradient (m/m)
K	Hydraulic conductivity (m/s)
L	Maximum length available inside the cadastral plot (m)
q	Groundwater velocity or Darcy velocity (m/s)
q_L	Heat flow rate per unit length of the borehole (W/m)
S	Heat source/sink term (W/m^3)
t	Elapsed time (s)
ΔT	Temperature change produced in the ground (K)
T	Average temperature of the porous medium (K)
W	Maximum width inside the cadastral plot (m)
x/y	Cartesian coordinates (m)

Greek symbols

ϕ	Integration variable
ρc	volumetric heat capacity of the subsurface (J/m^3/K)
$\rho_w c_w$	volumetric heat capacity of water (J/m^3/K)
$\lambda_{x/y}$	Effective thermal conductivity (W/m/K)