# Characterizing cadastral plots to optimize BHE exploitations

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**Keywords:** Thermal Plot, Borehole Heat Exchanger, Characteristic Thermal Curve.

## ABSTRACT

The uncontrolled implementation of shallow geothermal exploitations is starting to reduce their efficiency and sustainability. It is mandatory to develop specific management methodologies to register and control the exploitation of this energy resource. To ensure their widespread application, one of the properties of any management methodology must rely on simplicity, and, at the same time, the ability to reproduce the real behaviour of shallow geothermal exploitations.

In this work we present a methodology to control and limit the maximum shallow geothermal potential that can be extracted from a particular cadastral plot. It is a graphical method based on the geological, hydrogeological and geothermal properties of the area of interest.

According to the available space in the plot owned by the user, the optimal shallow geothermal potential is graphically calculated to adapt its area of thermal influence to the cadastral plot. This can be achieved with the Characteristic Thermal Curve, an automatically created graph that represents the extracted geothermal potential against the length and width of the thermal plume.

The optimal shallow geothermal potential will produced a thermal impact which should remain completely inside the plot. If the exploited shallow geothermal potential is greater than this optimal, the exploitation will deplete the energy resource of the user's plot. Thus, the neighbours could suffer thermal interferences, which will impact on the efficiency of their exploitations.

## 1. INTRODUCTION

Nowadays, the exploitation of shallow geothermal energy (SGE) is continuously growing. That is good news for the environment and also for current users: it is contributing to the reduction of greenhouse gasses emissions (Schiel et al., 2016) and household electric bills (Hee et al., 2013).

However, SGE is not an unlimited energy resource. There exists a maximum shallow geothermal potential that can be extracted to maintain and conserve the sustainability of this resource. The sustainability and efficiency of SGE exploitations depend on both, the exploitation itself and the neighbouring exploitations. On the one hand, if the extracted potential is greater than the thermal restoration capacity of soil, the long term efficiency could not be guarantee: the underground temperature will rise or drop constantly, reducing the efficiency along the useful life of the considered exploitation.

On the other hand, the optimal performance of SGE exploitations can be affected by the nearby ones. The extraction or dissipation of heat from the underground produce thermal disturbances (also known as thermal plumes) whose size and intensity depends on different variables, such as the extracted potential, the groundwater velocity and other geothermal parameters (thermal conductivity, heat capacity and thermal dispersion).

The expansion of SGE exploitations, both open and closed geothermal systems, is emerging without control. As a consequence, the thermal disturbances of geothermal exploitations can reach neighbouring exploitations. This leads to a depletion of the geothermal potential that can be exploited in order to maintain the efficiency and sustainability of existing SGE exploitations.

The damage between SGE exploitation has been found recently, with the boom of installations. Before, no one cared about this problem, when plenty of space where available to extract or dissipated heat. The management principle was limited to the rule “first come, first served” (Epting et al., 2013). In this situation, one of the advantages of SGE, its null visual impact, becomes a disadvantage when managing this resource. Without a geospatial database where existing exploitations are recorded, it is very difficult to know the position and potential of existing SGE exploitations. Therefore, one must always assume certain uncertainty when implementing new facilities, because of the ignorance about the real state of subterranean media.

To avoid this situation, it is imperative to implement a management methodology since the initial steps of SGE development. In these cases, most common management methodologies are challenging to implement, because they are based on numerical modelling. Numerical models are considered advanced techniques because of the requirement of two main aspects: specialist on this subject and a vast amount of data related to geological, hydrogeological and geothermal properties defining the initial and boundary conditions. Because of their scarcity, methods based on numerical techniques are relegated to mature markets of SGE, when there is enough information to build tough numerical models.

An example of a mature market of SGE is the city of Zaragoza (Spain), where García-Gil et al. (2015) proposed to establish a methodology based on numerical modelling to reassign the geothermal resources between existing and future exploitations.

In townships where this advanced technique could not be applied, it is mandatory to define alternative and simpler management methodologies to allocate the resource and satisfy the demand of renewable energy between current and future users.

In this work we propose and define a management methodology based on the Thermal Characteristic Curve, a graphical relation between the geothermal potential that can be extracted by Borehole Heat Exchangers (BHE) and the size of thermal plume produced by BHEs. Ideally, this methodology or other similar should be implemented by public administrations in order to settle a trustworthy framework to develop sustainable SGE markets.

An example of this methodology is developed for the township of Azul, with almost 60.000 inhabitants. It is located in the center of the Buenos Aires province, Argentina (Fig. 1). The urbanization of Azul is horizontal, characterized by single family homes.

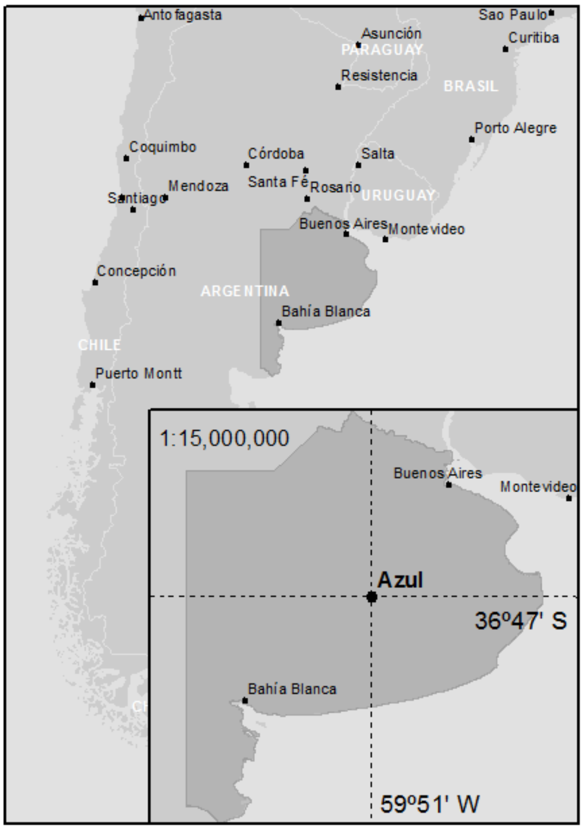


**Figure 1: Location map of Azul city in La Pampa area.**

## 2. MATERIALS

In this section, the main data required to implement the proposed methodology is presented.

### 2.1 Geological and hydrogeological settings

A basis geological and hydrogeological analysis is necessary to establish the main characteristics of subterranean media and then, to carry out a tough control and management of SGE. So first, the main aquifers and their geological, geothermal and hydraulic properties must be defined.

A lithological description defining the main geological units will provide of geothermal parameters, such as the thermal conductivity, the heat capacity and the thermal dispersion. These parameters are tabulated in bibliography and can be considered a good approximation when no field test is available (with the exception of thermal dispersion values). This is because their variation range is quite limited. Besides, in medium-high transmissive aquifers, the groundwater velocity has much more influence in the SGE potential than these geothermal parameters.

The hydrogeological analysis should be more accurate, due to the reason provided above. The groundwater velocity is a determining factor, mainly in sedimentary systems. However, it is easy to obtain: a piezometric surface and the hydraulic conductivity of the aquifer must be available. The piezometric map can be hand-draw from hydraulic head observations.

The groundwater velocity can be calculated by applying the Darcy's Law.

The piezometric surface is also necessary to create the groundwater flow net. By knowing the groundwater flow direction, the thermal plume can be oriented inside the plot to optimize SGE potential extraction.

The main hydrogeological unit in Azul city is the Pampean aquifer, with a sandy loam composition. The basement can be found between 111 and 143 m depth. This main aquifer presents local heterogeneities which can alter the hydraulic and geothermal parameters. The available piezometric surface for Azul city can be consulted in Fig. 2. It was defined in previous studies by Cazenave et al. (2005).

As a result of the previous geological and hydrogeological analysis, the variables contained in Table 1 should be available. This table contains the values used for the study area of Azul.

**Table 1: Hydraulic and geothermal parameters considered for the study site. Source: Cazenave et al. (2005) and Schön (2011).**

| Parameter | Value | Unit |
|---|---|---|
| Hydraulic conductivity | $5.8 \cdot 10^{-5}$ | m/s |
| Thermal conductivity | 2.7 | W/m/K |
| Volumetric Heat Capacity | $2.8 \cdot 10^{6}$ | $J/m^3/K$ |
| Thermal dispersion | 10/1 | m |

## 2.2 Cadastral plot distribution

The objective of this methodology is to avoid thermal interferences between exploitations. This can be achieved by circumscribing the thermal plume inside the available surface, which can be represented by the cadastral plot.

This information is usually provided by municipalities, and can be even consulted online with web map services. The cadastral plots defined in Azul city are shown in Fig. 2.

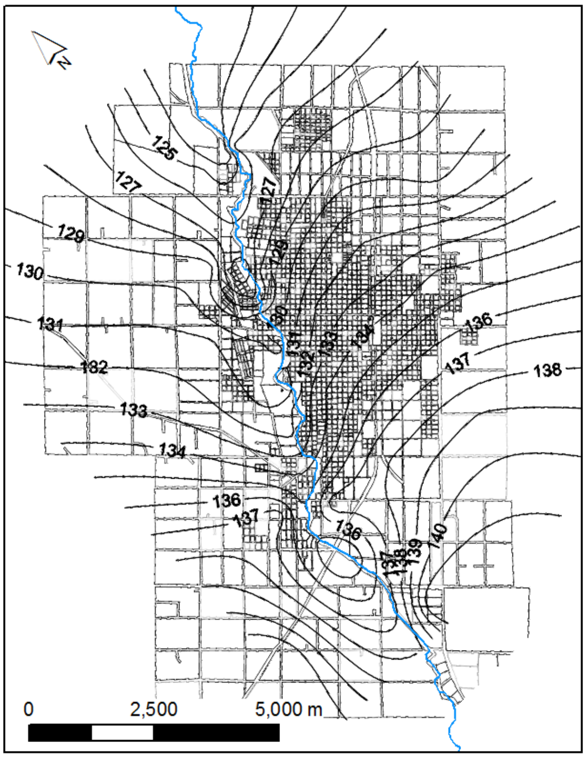


**Figure 2: Piezometric surface and cadastral plot distribution for the city of Azul. Source: Cazenave et al. (2005).**

## 2.3 Description of the Thermal Characteristic Curve (TCC)

The Thermal Characteristic Curve (TCC) shows graphically the thermal respond of underground when SGE is being exploited by a Borehole Heat Exchanger (BHE). It is a SGE potential vs. thermal plume length graph.

This relation is obtained from an analytical solution of the heat transport equation in porous media (de Marsily, 1986) [1]:

$$\rho c\, \frac{\partial T}{\partial t} + q\, \rho_w c_w \frac{\partial T}{\partial x} - \lambda_x \frac{\partial^2 T}{\partial x^2} - \lambda_y \frac{\partial^2 T}{\partial y^2} - S = 0 \qquad [1]$$

where *T* is the temperature as the state variable (*K*), *q* is the groundwater velocity, also known as Darcy velocity (*m/s*), $\rho c$ and $\rho_w c_w$ are the volumetric heat capacity of subterranean media and water (*J/m³/K*), $\lambda_{x/y}$ is the effective thermal conductivity in the longitudinal and transverse direction, *x/y* are the Cartesian coordinates, *t* is the time (*s*) and *S* is the heat source/sink term ($W/m^3$). Equation [1] has been solved under different conditions by assuming particular models. In this work, the analytical solution proposed by Molina-Giraldo et al. (2011) was implemented to create the TCC [2].

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

where $\phi$ is the integration variable, $\Delta T$ is the temperature increment produced in the ground ($K$) and $q_L$ is the heating rate or SGE potential ($W/m$).

The analytical solution [2] assumes a Moving Infinite Line Source Model (MILS) to represent the BHE. It allows considering groundwater flow through advection and dispersion heat transport mechanisms. This expression can be reformulated to express the shallow geothermal potential, $q_L$, as a function of the thermal plume size, $f(x,y)$. The new expression is presented in Equation [3]:

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

The TCC represents $q_L$ vs $x, y$. In order to obtain this graph, additional information must be establish by the administration: the variables $\Delta T$ and $t$. These variables are named Constraining variables. They represent the uncertainties of the geological, hydrogeological and geothermal models. More conservative values of these variables should be assumed in poorly defined systems.

The temperature increment, $\Delta T$, represents the threshold upon which a thermal affection is considered. The thermal plume encloses an area where the BHE produces a temperature increment greater than $\Delta T$. The more reliable the conceptual model describing the behavior of underground is, the higher the $\Delta T$ value.

The second variable, $t$, represents the elapsed time since the start of SGE exploitation. For instance, it can be assumed a six month period.

Fig. 3 contains a synthetic representation of the TCC. The distance available will define the maximum SGE potential that could be exploited in the considered plot. In those cases when the BHE can be drilled anywhere inside the plot, the limiting distance would correspond to the Distance available variable, defined in Figure 1. In other cases, according to groundwater flow net and the feasible sites to drill, the limiting distance can be identified as the Distance upstream or Distance downstream variables in Figure 1. Additionally, with these two last variables, the BHE position can be demarcated.

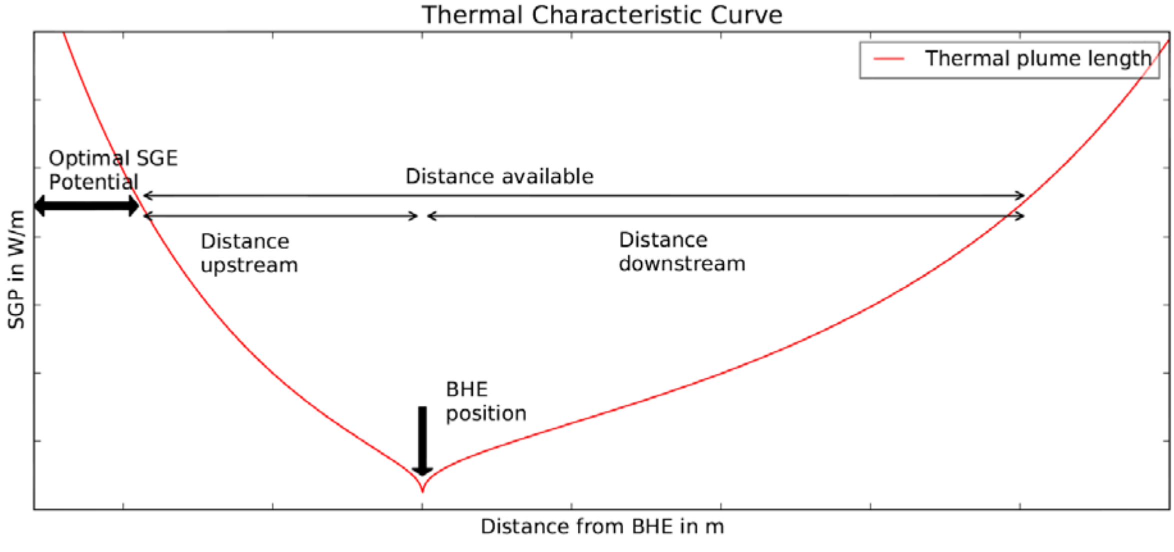


**Figure 3: Schematic representation of Thermal Characteristic Curve (TCC). It represents the relation between the SGE potential and the size of the thermal plume produced.**

The TCC can be created automatically with a Python script available on Alcaraz et al. (2016).

### 3. METHODS

In this section, the main processes of the proposed methodology are presented, assuming that the main data previously described are available for the township.

These processes are divided in two main focuses. The first processes (3.1. and 3.2) are oriented to the metropolitan scale, because they involve the complete area for SGE management, i.e., the whole township extension.

These metropolitan processes must be accomplished at least just one time, at the beginning of the SGE management. They must be performed by the administration that controls the SGE resources. The input and output information must be updated with a certain periodicity.

The second processes (3.3. and 3.4) are focused on the local scale, where the particularities of the cadastral plot can be examined.

These local processes will be repeated whenever there is a new application for BHE drilling. They must be executed by the BHE installer and validated by the administrator that must approve the concession.

### 3.1 Groundwater velocity

Once the affected aquifers and their piezometric surface are defined (the piezometric surface must be available as raster data format over the whole domain of interest), the groundwater velocity of each aquifer can be obtained by applying the Darcy's Law [4]:

$$q = K \cdot i \qquad [4]$$

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 hydraulic gradient can be obtained from the piezometric surface as the slope of this surface. This can be calculated with GIS standard tools.

The hydraulic conductivity in Azul city is 5.8E-5 m/s. The groundwater velocity is shown in Fig. 4. The hydraulic gradient was obtained as the slope of the piezometric surface and multiplied by the hydraulic conductivity to calculate the Darcy velocity.

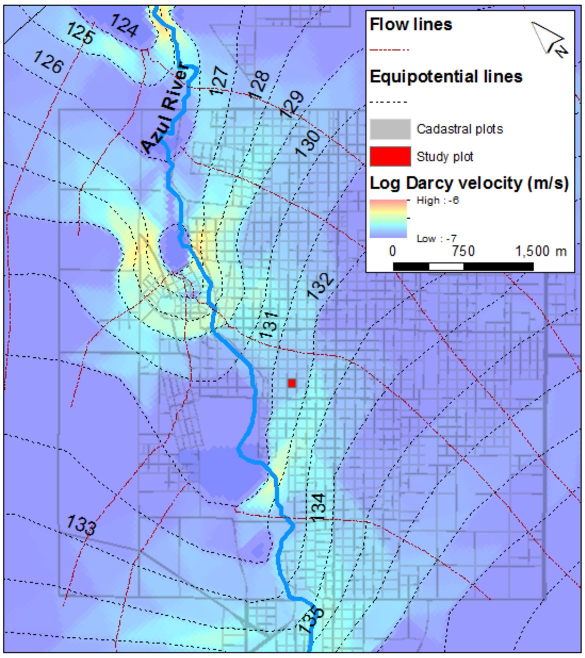


**Figure 4: Darcy velocity map and groundwater flow net for Azul city. The study plot is highlighted in red colour.**

### 3.2 Groundwater flow net

The administration also must provide the groundwater flow net. It can be obtained from the piezometric surface and defines the groundwater flow direction. The thermal plumes will be oriented according to this direction.

The relation between the flow net and the shape and orientation of the cadastral plot will be a determinant factor to characterize the cadastral plot. Those plots whose longitudinal dimension is parallel to groundwater flow can achieve higher level of SGE potential.

The flow lines defining the groundwater flow net can be obtained with GIS tools but also can be hand-drawn with lines perpendicular to equipotential lines.

The groundwater flow net for the Azul city is shown in Fig. 4, defined by their flow and equipotential lines.

### 3.3 Limiting distance

First of all, the cadastral plot must be analysed in order to differentiate the feasible areas to drill the BHE inside the cadastral plot. Technical criteria must be taken into account, such as the accessibility of the borehole drilling rig or the existence of subterranean infrastructures (supply network pipes). Once the feasible area to drill is defined, the flow net must be overlapped.

The maximum distance available inside the cadastral plot must be parallel to groundwater flow lines ($L$). This distance will define the maximum length of the thermal plume that BHE can produce. The distance $L$ encloses both the Distances Upstream and Downstream.

The maximum distance perpendicular to $L$, denoted as $W$, will define the maximum width of the thermal plume. In a similar way to distance $L$, distance $W$ encloses the distances at both sides of the longitudinal thermal plume axis.

These dimensions, $L$ and $W$, will characterize the cadastral plot under analysis. They are necessary to define the maximum SGE potential that can be extracted in a sustainable manner from the cadastral plot. These distances can be obtained by GIS standard tools.

As it was mentioned above, the work scale at this point is reduced. The following steps are focused on a local scale. The installer must zoom in to the cadastral plot of interest, whose position is shown in Fig. 4.

Fig. 5 shows the $L$ and $W$ distances for the particular cadastral plot highlighted in Fig. 4. The cadastral subplot under analysis has no restrictions for drilling. Its dimensions are $L$ = 35 m long and $W$ = 20 m wide. The BHE installer should lead with this information in order to dimension the SGE exploitation.

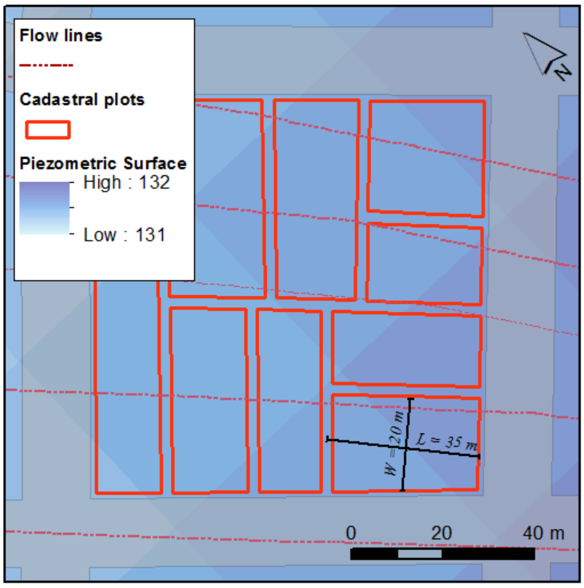


**Figure 5: Cadastral plot of study with the maximum distances available *L* and *W*.**

### 3.4 SGE potential

At this stage, the BHE installer has to elaborate the Thermal Characteristic Curve (TCC). Ideally, the TCC could be created by an online map application developed by the public administration. If the TCC is not accessible, the installer could create it with the Python script available at Alcaraz et al. (2016).

To create the TCC it is necessary that both Constraining variables, $\Delta T$ and $t$, are established by the administrator. The threshold related to the variable $\Delta T$ was defined as 0.1K, a very restrictive value because of the uncertainties of the hydrogeological model. The parameter $t$ is 6 months, assuming the BHE is going to equally interchange between cool and heat modes.

Once the Constraining variables are defined and the data contained in Table 1 is available, it is possible to obtain the TCC for the cadastral plot of interest. This TCC is shown in Figure 6.

The TCC gives information of different kind. First of all, it supports the dimension of the maximum SGE potential that can be extracted. In this case, according to the *L* and *W* dimensions, the optimal SGE potential is 70 W/m. However, with the TCC the installer is able to know the distance of thermal affection for whatever SGE potential.

Moreover, the TCC defines the BHE position by establishing the distance upstream and downstream. For the cadastral plot of interest, these distances are 15 and 20 m respectively.

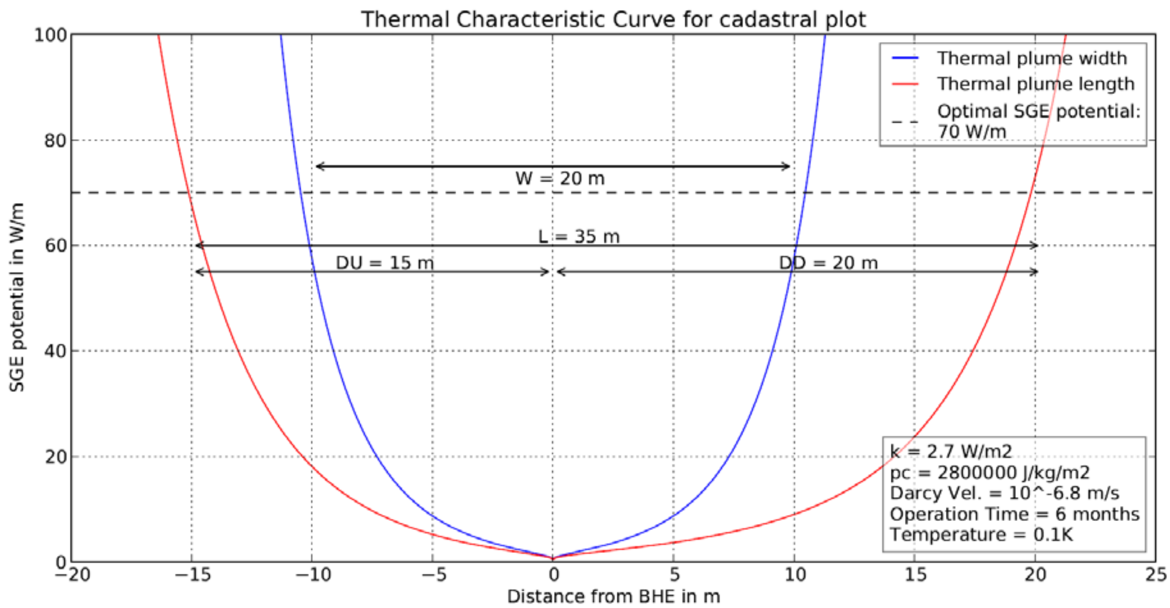


**Figure 6: Characteristic Thermal Curve (TCC) for the cadastral plot of interest. It represents the optimal shallow geothermal potential against the available distance inside the cadastral plot.**

In those cases where the limiting dimension is the width or transverse dimension, the TCC also shows the thermal plume width. The dimension *W* must fit with this curve, in blue colour on the TCC, whereas the dimension *L* must fit the red colour curve.

The blue curve represents the width of the thermal plume at the BHE position. So, it is expected to get greater values of the thermal plume wide downstream of the BHE.

To solve this issue, we recommend drawing the thermal plume over the cadastral plot in a GIS environment. Specific tools were developed with this objective in Alcaraz et al. (2016).

### 4. CONCLUSIONS

An accessible methodology to manage SGE is presented. It requires a basic hydrogeological study based on a piezometric surface and the geological description of the exploited aquifer. Local administration has to define the threshold upon which this management is based on. Additional data about the cadastral plots distribution is also required.

With this information it is easy and fast the definition of optimal SGE potential that can be exploited with BHE. It is based on the Thermal Characteristic Curve, a SGE potential vs thermal distance graph.

The required tools to implement this methodology are available here and in previous studies as Python scripts. It is highly recommended to work inside a GIS environment to cope with the geographical characteristics of data.

The example presented for the Azul city validates the implementation of this methodology when a basic hydrogeological analysis is available. However, further conclusions about SGE in Azul city cannot be obtained from this work: it would be necessary to update the existing studies related to geological and hydrogeological properties.

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