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Estimating Low-Enthalpy Geothermal Energy Potential in Four Cities of Southern Chile: A Battle against Particulate Material Pollution

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ABSTRACT

The majority of cities located in central and southern Chile are highly polluted with particulate material. This problem is originated by the use of firewood as a heating source. Without the necessary ventilation, large and medium cities such as Santiago, Talca, Temuco and Osorno reach high PM10-PM2.5 concentrations, well above any national or international norm.

In order to reduce the emission of PM within the next decade, we propose the use of geothermal heat pumps (GHPs) as an environmentally friendly alternative. This work aims to compare the available energy for closed and open loop systems in four cities of central-southern Chile. We discuss the possibilities for implementing scalable prototypes in these cities and their possible impact in PM emissions.

An hydrogeological analysis was performed in each city including i) data gathered from the national water agency (*Dirección General de Aguas*; DGA) and ii) data measured in shallow wells (water temperature, static level and electrical conductivity). The data was then used to calculate available energy for open systems. Thermal properties of soils (thermal conductivity, thermal diffusivity and specific heat) were measured in each city and the data was used to calculate available energy for closed systems. Available data was analyzed in a Geographic Information System (GIS). The comparison of available energy for open and close loops was then analyzed in the light of each city's urban configuration (available space, energy demand, etc.).

Static levels in Santiago range between 2.5 and 165 m depth. In Talca, Temuco and Osorno static level varies from 3 to 45 m depth. Hydraulic transmissivities are similar in Santiago and Talca, ranging between 10 and 7000 m2/day with temperatures ranging from 15 to 19 ºC. Temuco and Osorno on the other hand, show a wider spectrum of transmissivities ranging from 1 to 1000 m^2/day with temperatures ranging from 13 to 14 ºC.

Given the high hydraulic gradient and groundwater recharge present in south-central Chile, there is great potential for the use of this resource implementing geothermal heat pump systems. Although variability exists in some parameters, the values measured in this study suggest that GHP could help mitigate air pollution in all the prospected areas.

1. INTRODUCTION

The majority of cities located of central and southern Chile are highly polluted with particulate material due to the use of firewood as a heating source. Without the necessary ventilation, large and medium cities such as Santiago, Talca, Temuco and Osorno reach higher PM10-PM2.5 concentrations every year, well above any national or international norm.

The emissions of particle material (PM10, PM2.5) due to wood combustion represent a growing problem in air quality in main Chilean cities where the mean temperature drastically decreases during fall-winter months. In consequence, the use of wood, specially wet wood, has generated that out of the 15 most polluted cities in Latin America, 9 are from Chile (Airvisual World Air Quality Review, 2018). This critical fact adds to the low ventilation rates in each one of these cities, besides the low availability of companies that supply clean and sustainable solutions for heating. This conjunction of circumstances constitutes a challenging problem for regional and national public institutions, which have to account for immediate problems, such as high demand for thermal comfort and particle material pollution.

A Geothermal Heat Pump (GHP) is a local, reliable, resilient, environmentally-friendly, and sustainable thermal energy source for cities (Soltani et al., 2019). The efficiency of the GHP is constrained by the *Coefficient of Performance* (COP), which is the ratio of thermal output and electric input for the GHP functioning. A geothermal heat pump is composed of a Geothermal Heat Exchanger (GHE) coupled with a water-to-water heat pump. There are different types of GHE, and they can be open loop or closed loop systems. The open loop system is usually called Groundwater Heat Pump system (GWHP or GWHE *Groundwater Heat Exchanger*), consists of extracting groundwater to exchange its heat in the heat pump and inject it back into the aquifer to keep the hydraulic head stability. On the other hand, the closed loop system usually called Ground Source Heat Pump system (GSHP or BHE for *Borehole Heat Exchanger*) is a closed array of pipes buried, either horizontally or vertically, which exchanges heat in the heat pump (Florides and Kalogirou, 2007). The COP for an open loop system is higher than for a closed loop system because of the contact surface between the GSHE and the underground. Consequently, for vertical systems, the drilling meters for closed loop systems is higher than open loop system, which impacts the installation costs.

To establish the potential to install GHP in four of the most polluted Chilean cities, we carried out an assessment of the geothermal energy that can be recovered depending on the GSHE. The amount of energy that can be recovered with GHP, depends thermal properties of the shallow geological sequences, along with the groundwater availability and hydraulic properties of the aquifer. Therefore, depends on the geological and hydrogeological setting. On one hand, thermal properties of rock and sediments and saturate condition, constrains the heat exchange between BHE and the underground. Thermal properties of rock and sediments strongly depend on lithology (VDI 2004). On the other hand, hydraulic properties constrain the pumping/injection rate and, therefore, thermal power availability. It must be considered, the assessment is for highly densely populated cities, thus horizontal closed loop system is not considered.

In order to reduce the emission of PM within the next decades, we propose the use of geothermal heat pumps (GHPs) as an environmentally friendly alternative. Based on comparison of available energy that can be recovered with closed and open loop systems in the cities, we discuss the possibilities for implementing scalable prototypes and their possible impact in PM emissions.

1.1 Geological framework

The **Santiago basin** is located in central Chile (33ºS to 34ºS). In the most populated area, there are more than 6.5 million inhabitants that represent ca. 40% of the total Chilean population (XVIII Chilean Census, 2012). It is located between the Main Andean Range and Coastal Range (Fig. 1a). The Coastal Range is located west of the Santiago basin and is composed mainly by Cretaceous volcanic rocks and Jurassic to Cretaceous intrusive rocks (Gana et al., 1996; Wall et al., 1999). The Main Andean Range is located east of Santiago basin and corresponds mainly to Eocene to Miocene volcanic rocks and Miocene to Oligocene intrusive rocks (Thiele R. 1980; Wall et al., 1999; Sellés D. 2000; Sellés and Gana 2001). The sedimentary infill of the Santiago Basin is composed of alluvial, fluvial and isolated lacustrine sediments, with pyroclastic interbedded layers. The main source of clastic sediments is the Main Andean Range (Muñoz et al., 2015 and references therein, Figure 1). The main structure of the eastern part of Talca basin is the San Ramón Fault System, which is a west verging reverse fault system controlling the eastern edge of the basin (Armijo et al., 2010).

The climate of Santiago is Subtropical Tempered with dry and warm summer (Köppen, W., 1918; Peel et al, 2007). The annual mean temperature is 13.6 ºC ranging from 0 ºC in winter to 34 ºC in summer (Santibañez & Uribe 1990). The average annual rainfall is about 300 mm per year, concentrated mainly from May to August.

The **Talca basin** is located between the Andean Range by the east and Coastal Range by the west, in central Chile (35°S). The most populated city in the basin is Talca city with 227,674 inhabitants (XVIII Chilean Census, 2012). The western part of the Andean Range is composed of Cenozoic volcanic rocks intruded by Miocene batholiths. The Coastal Range is composed of Paleozoic metamorphic rocks, and Jurassic intrusive rocks in the west, and Mesozoic volcanic rocks intruded by large Mesozoic granitic bodies in the east. The sedimentary infill of Talca basin is composed by gravel-sized fluvio-alluvial and fluvial deposits (Hauser, 1995; Figure 1). Pleistocene to Holocene pyroclastic deposits cover a wide area of the northern part of the basin. The main structure of the eastern part of Talca basin is the San Ramón Fault System, which is a west verging reverse fault system controlling the eastern edge of the basin (Armijo et al., 2010). The main Coastal Range encompass the Litu Fault System, which is a normal fault system with N10-15E direction (Bravo, 2001).

The climate of Talca is Mediterranean with dry and warm summer. The annual mean temperature is 14.2 ºC ranging from -2 ºC in winter to 32 ºC in summer. The average annual rainfall is about 676.2 mm per year, concentrated mainly from May to August. This region hosts over two hundred thousand people (Chilean census 2017).

The **Temuco Basin** is located within the Coastal range in the central-south Chile (38°S-39°S). The most populated city in the basin is Temuco city with 287,850 inhabitants (XVIII Chilean Census, 2012). The basement of the basin consists mainly of Paleozoic-Triassic metamorphic rocks underlying the Triassic to Pleistocene sedimentary sequences (Elgueta & Rubio, 1989). The sedimentary infill of Temuco basin is composed manly by partially-consolidated glacier sediments at the bottom and alluvial, fluvial sediments in the middle to upper portion of the non-consolidated stratigraphic sequence. There are pyroclastic interbedded layers within the non-consolidated sedimentary sequence (Rubio, 1993). The groundwater hosted in aquifers constituted by the sedimentary infill provide fresh water for domestic usage and industrial purposes (Figure 1).

The climate of Talca is Oceanic with short and warm summer. The annual mean temperature is 11.2 ºC ranging from -2 ºC in winter to 29 ºC in summer. The average annual rainfall is about 1150.1 mm per year, concentrated mainly from April to September.

The **Osorno Basin** is located between the Andean Range by the east and Coastal Range by the west (40ºS-41ºS). The most populated city in the basin is Osorno city with 161,000 inhabitants (XVIII Chilean Census, 2012). The infill non-consolidated sedimentary deposits are from Pleistocene to quaternary ages and cover an area of about 2,500 km^2, with a maximum thickness of 1,500 m. These deposits are from glacio-fluvial environment (e.g. Santa María deposits) with pyroclastic-epiclastic interstratified sequences (e.g. San Pablo sequence). The basement of the sedimentary sequence beneath Osorno city is the Santo Domingo Formation, a marine sedimentary sequence of Miocene age (Figure 1).

The climate of Osorno is Oceanic with short and warm summer. The annual mean temperature is 12,6 ºC ranging from -3 ºC in winter to 29 ºC in summer. The average annual rainfall is about 1327.7 mm per year, concentrated mainly from April to October.

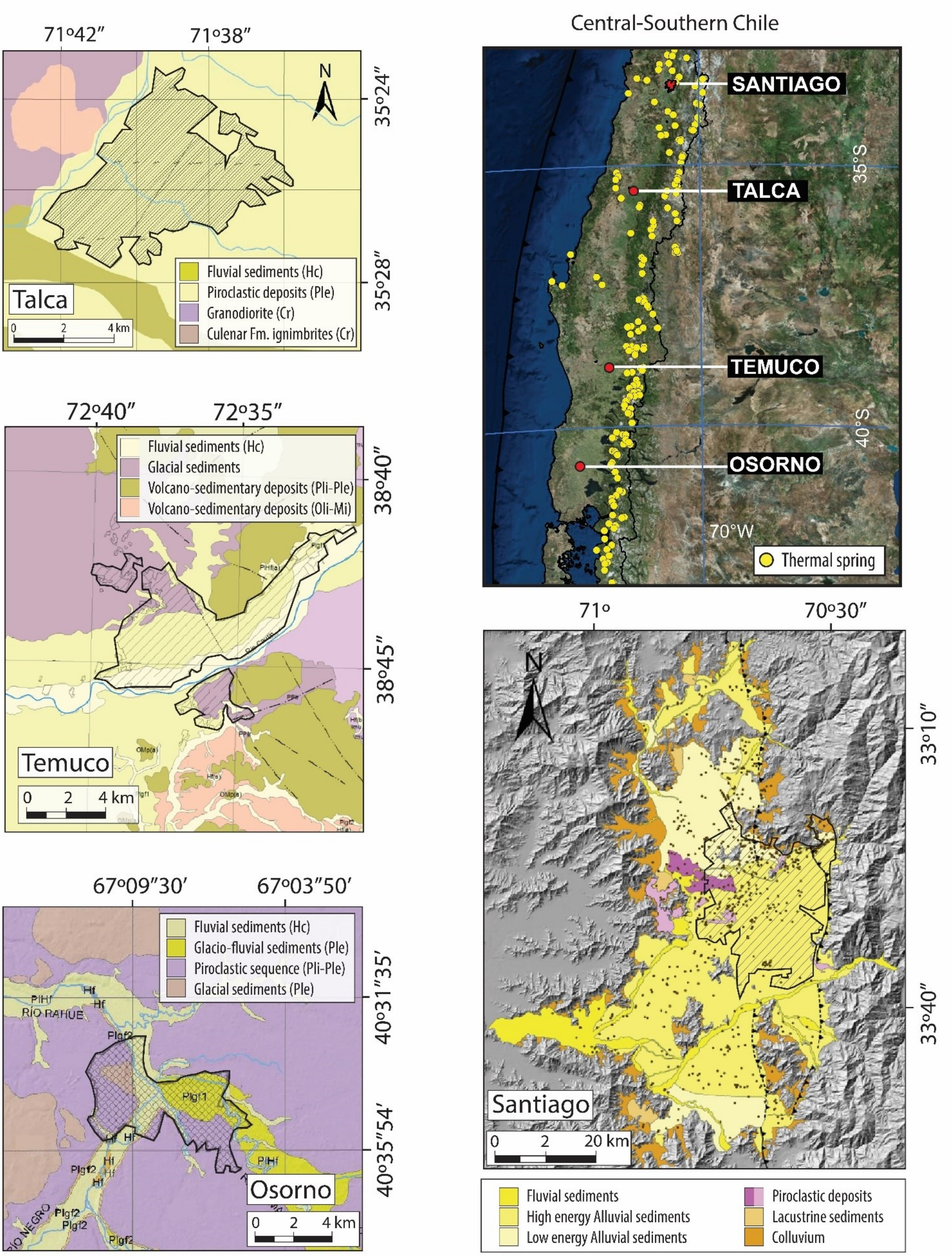

Figure 1:Location and geological context of each city included in this study. Hc: Holocene, Pli: Pliocene, Ple: Pleistocene, Cr: Cretaceous.

2. METHODS AND DATA BASE FOR ASSESSMENT

In this work, we compared the amount of thermal energy, which can be recovered by GHP with open and closed vertical systems in 4 cities of central southern Chile (Figure 1). For this, we considered the use of one borehole in the case of BHE and two wells in the case of GWHE (one pumping well and one injection well). However, for higher thermal energy demand, it is necessary to evaluate several BHE and their distribution. Thermally affected areas depend on the amount of heat exchanged and groundwater flow velocity, which are not considered in this work.

2.1 Data base for the assessment result treatment

The amount of thermal energy that can be recovered is assessed for each location, where a groundwater well has been drilled. The record of location of groundwater wells is available at the Directorate General of Water (Dirección General de Aguas, DGA). Database for the assessment includes: i) database from DGA, which is composed by stratigraphic profiles, groundwater table, pumping test and caudal extractable; and ii) up to date novel measurements of groundwater table, besides temperature and electric conductivity profiles in shallow wells. The groundwater table along with temperature and electrical conductivity profiles are measured with a Solinst 107 TLC probe.

Once the amount geothermal energy is calculated for open loop and closed loop systems, a statistical analysis is performed with ordinary kriging, which is an algorithm that optimizes the interpolation dividing the spatial variation into three components: deterministic variation, spatially autocorrelation and uncorrelated noise. Afterwards, the comparison of available energy for open and close loops is then analyzed in the light of geological context of each city.

2.2 Groundwater Heat Exchanger (GWHE)

The Groundwater Heat Pump system (GWHP), consists of extracting groundwater to exchange its heat in the heat pump, and inject it back into the aquifer to keep the hydraulic head stability. Therefore, the energy that can be extracted strongly depends on the pumping/injection rate. The power obtained from groundwater is calculated as follows (eq. 1):

$$P = \mathrm{Q} \cdot \rho \cdot C_p \cdot \Delta\mathrm{T} \qquad (1)$$

Where P is thermal power (W), Q is pumping rate (m^3/s), ρ is water density (kg/m^3), C_p is the specific heat capacity of water at constant pressure (4.183 J/kgK) and ΔT is the difference between the inlet and outlet groundwater temperatures (5 ºC). Since the GHP will be used only for heating, available power is finally multiplied by 5/4 to simulate a COP of 5 (Chua et al., 2010; Self et al., 2013; Aravena et al., 2015).

2.3 Borehole heat exchanger (BHE)

The BHE consists of a borehole with a U-shape pipe inside, in which a fluid circulates, exchanging heat with the ground. This heat exchange depends on thermal properties of soil, its water content and groundwater velocity. The energy that can be exchanged per meter by a BHE was defined by the VDI 2004 as the specific Heat Extraction (sHE) in units of Watts per meter (W/m). To be conservative 2,400 operating hours are considered (Table 1).

As the sHE is variable in each layer is strongly dependent of water content and its velocity, for each borehole with stratigraphic information, an upper specific Heat Extraction for dry sediments (sHEd) and a lower saturated specific Heat Extraction for saturated sediments (sHES) were determined as follows

$$\mathrm{sHE}_d = \frac{1}{\mathrm{Th}_d}\sum_{i=1}^{k}(\mathrm{sHE}_i \cdot \mathrm{Th}_i) \qquad \text{if } \Sigma\,\mathrm{Th}_i > \text{groundwater table} \qquad (2)$$

$$\mathrm{sHE}_s = \frac{1}{\mathrm{Th}_s}\sum_{i=k+1}^{n}(\mathrm{sHE}_i \cdot \mathrm{Th}_i) \qquad \text{if } \Sigma\,\mathrm{Th}_i < \text{groundwater table} \qquad (3)$$

Here Th_d and Th_s are dry and saturated thickness respectively, sHE_i is the specific Heat Extraction of the layer i, Th_i is the specific Heat Extraction of the layer i and k is the layer just above static level depth. The obtained sHE_d and sHE_s are used to calculate the available energy for a BHE with a 50m depth well and a COP of 4 in each city.

Table 1: Typical values of specific heat extraction for sediments (VDI 2004)

Soil type	Specific heat extraction after 2,400 operating hours (Watt/m)
Gravel, sand, dry	<20
Gravel, sand, water saturated	55-56
Gravel, sand with strong groundwater flow	80-100
Clay, silt, mud	30-40

3. RESULTS

3.1 GWHE

Groundwater table in Santiago ranges between 2.5 and 165 m depth with an average value of 55m. In Talca, Temuco and Osorno the groundwater table varies from 0 to 45 m depth. Hydraulic transmissivities are similar in Santiago and Talca ranging between 10 and 7000 m^2/day with temperatures ranging from 15 to 19 ºC. Temuco and Osorno, show a wider spectrum of transmissivities ranging from 1 to 1000 mm^2/day with temperatures ranging from 13 to 14 ºC.

In Santiago, 50% of assigned pumping rates are well above 2 L/s. Nevertheless, this value rises up to 10 L/s if we consider only the data located inside the main hydrological basin (Río Mapocho). The available thermal power of one 10 L/s well, coupled with a heat pump, is about 219 kW. The central and north parts of the basin host the high favorability areas, where the better wells allow to produce up to 600 kW of thermal power and the groundwater table is lower than 20m. In addition, some individual wells surpass 1 MW of available power (Figure 2). The eastern part of the basin shows a favorable setting with high power potential but deep groundwater table (more than 80m depth).

In Talca, 50% of assigned pumping rates are above 27 L/s, corresponding to an available thermal power of 567 kW per well, many individual wells surpass 1 MW of available thermal power and most urban areas show a high favorability due to an aquifer with a groundwater table at less than 25m depth (Figure 2).

In Temuco the average thickness of the aquifer is 65m. 50% of assigned pumping rates are above 1.5 L/s, corresponding to an available thermal power of 18.8 kW per well. Nevertheless, few individual wells surpass 1 MW of available power. The western part of the urban area has a high favorability with available power above 600 kW per well and groundwater table lower than 30m depth (Figure 2).

In Osorno, 50% of assigned pumping rates are above 5.4 L/s, corresponding to an available thermal power of 135 kW, some individual wells surpass 1 MW of available power. Most of the city has a high favorability with available power above 200 kW per well (Figure 2). The static level varies from 6 to 45 m, deepening from east to west (Figure 2).

3.2 BHE

In the Santiago basin, sHE values range from 26 to 77 (W/m) and available power per 50m well varies from 1.34 to 5.57 kW. The western side of the basin has a high favorability with most wells showing a potential over 4 kW (Figure 3). In the eastern side of the basin wells has a power potential of less than 2 kW.

In the Talca basin, sHE values range from 43 up to 86 (W/m) in areas with a high groundwater velocity. Available power per 50m well varies from 1.7 to 5.3 kW. Most of the urban area has a high favorability with power potential above 4.6 kW per well. Only a small segment in the north-east side of the city shows power potential below 4.6 kW per well (Figure 3).

In the Temuco basin, sHE values range from 35 (W/m) up to 80 (W/m) in areas with a high groundwater velocity. Available power per 50m well varies from 3.2 to 5.0 kW (Figure 3). The western and central-northern parts of the city have a high favorability with power potential above 4.4 kW per well. The areas of the city located towards the south and south-east of the basin have a lower favorability with power potential below 4.4 kW per well.

In the Osorno basin, sHE values range from 31 to 78 (W/m) and available power per 50m well varies from 1.7 to 5.3 kW. Most of the urban area has medium to high favorability with power potential ranging from 3.1 to 4.6 kW per well. Available energy tends to increase eastward and directly south of the city (Figure 3).

Table 2: Summary of hydrogeological parameters and available energy calculated for GWHP and BHE systems (only considers urban areas).

	GWHP						BHE					
	groundwater temperature (ºC)		Aquifer Transmissivity (m2/day)		Available energy (kW per well)		static level (m)		sHE (W/m)		kW per 50m WELL	
	min	max	min	max	min	max	min	max	min	max	min	max
Santiago	13,8	19,0	10,0	5000,0	<50	1300	2,5	165,0	25,7	77,1	1,3	5,6
Talca	15,8	19,2	100,0	7300,0	<50	650	0,0	33,0	43,0	86,0	1,7	5,3
Temuco	12,8	14,8	2,0	1150,0	<50	3000	3,0	30,0	35,0	58,0	3,2	5,0
Osorno	13,3	14,0	1,0	1100,0	<50	1900	5,5	44,6	37,3	66,1	3,1	4,6

4. DISCUSSION

In Santiago and Talca, temperature of groundwater is in average 4ºC higher than in Temuco and Osorno. This is consistent with higher atmospheric mean annual temperatures in the northern cities were a higher COP is also expected. Additionally, cold season is much longer in Temuco and Osorno, so a higher heat load is expected when compared with Santiago and Talca.

BHE system are usually less efficient in performance (COP) when compared with a GWHP. Nevertheless, the isolated nature of the pipe array prevents the contact with the surrounding aquifers, which could be a crucial factor in areas with restricted pumping rates. We suggest BHE are in order when underground water is scarce or undetermined. Nevertheless, the majority of prospected areas have aquifers with good hydraulic properties for the use of GWHP, allowing to obtain more than 10 times the amount of energy that can be obtained from BHE.

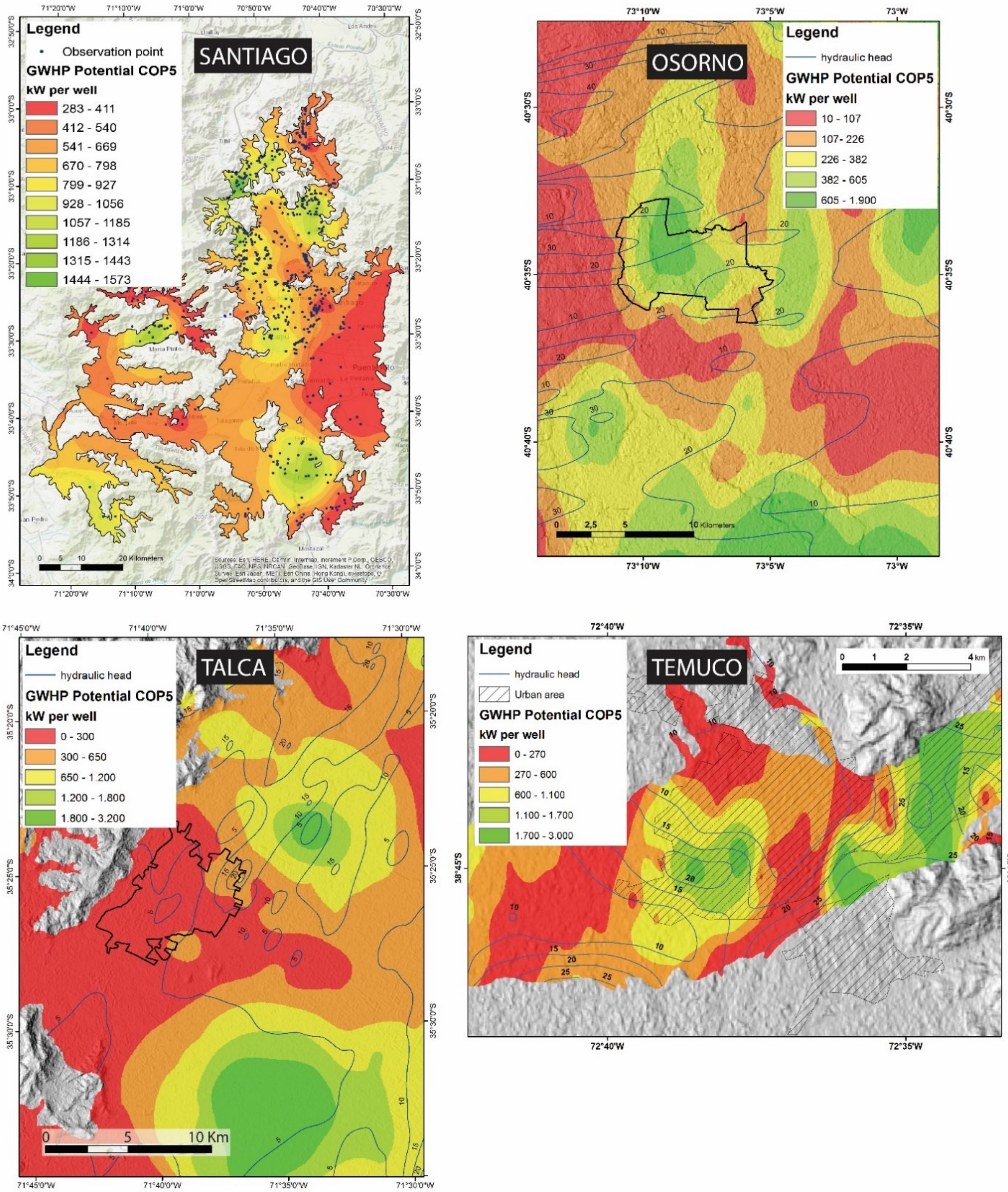

Figure 2: Available energy for GWHP systems in Santiago, Talca, Osorno and Temuco.

The key parameter that improves the heat exchange, either in open and closed loop systems, is the availability of groundwater and aquifer hydraulic conductivity, which controls the groundwater flow velocity. The above is clear in the case of Santiago and Talca basin, where the aquifer is manly composed of sediments from alluvial environment (see geological framework). The alluvial sediments are composed mainly of sand and gravel layers (Reading, 2009), which have hydraulic conductivity in the range of 1 to 10^4 m/day (Custodio and Llamas, 1983). In contrast the aquifer in Temuco and Osorno is composed by sediments from fluvio-glacial environment (see geological framework). The fluvio-glacial sediments are composed of massive to sub-horizontally bedded gravels with thin and sparse fine grained units (Reading, 2009). The above produce thin permeable layers with fine grain relatively impermeable interbedded layer, which have hydraulic conductivity in the range of 10^{-3} to 10 m/day (Custodio and Llamas, 1983).

It is important to note that, in all 4 cities, there are some reduced areas where, despite having a shallow static level, there is a low favorability for GWHP and BHE. This is mainly because of the low hydraulic conductivity encountered in some low-energy alluvial fans, lacustrine, and pyroclastic deposits. This lithological control is enhanced in Temuco an Osorno, were glacial deposits are present, reflecting on a lower maximum transmissivity when compared with the basins located further north, Santiago and Talca.

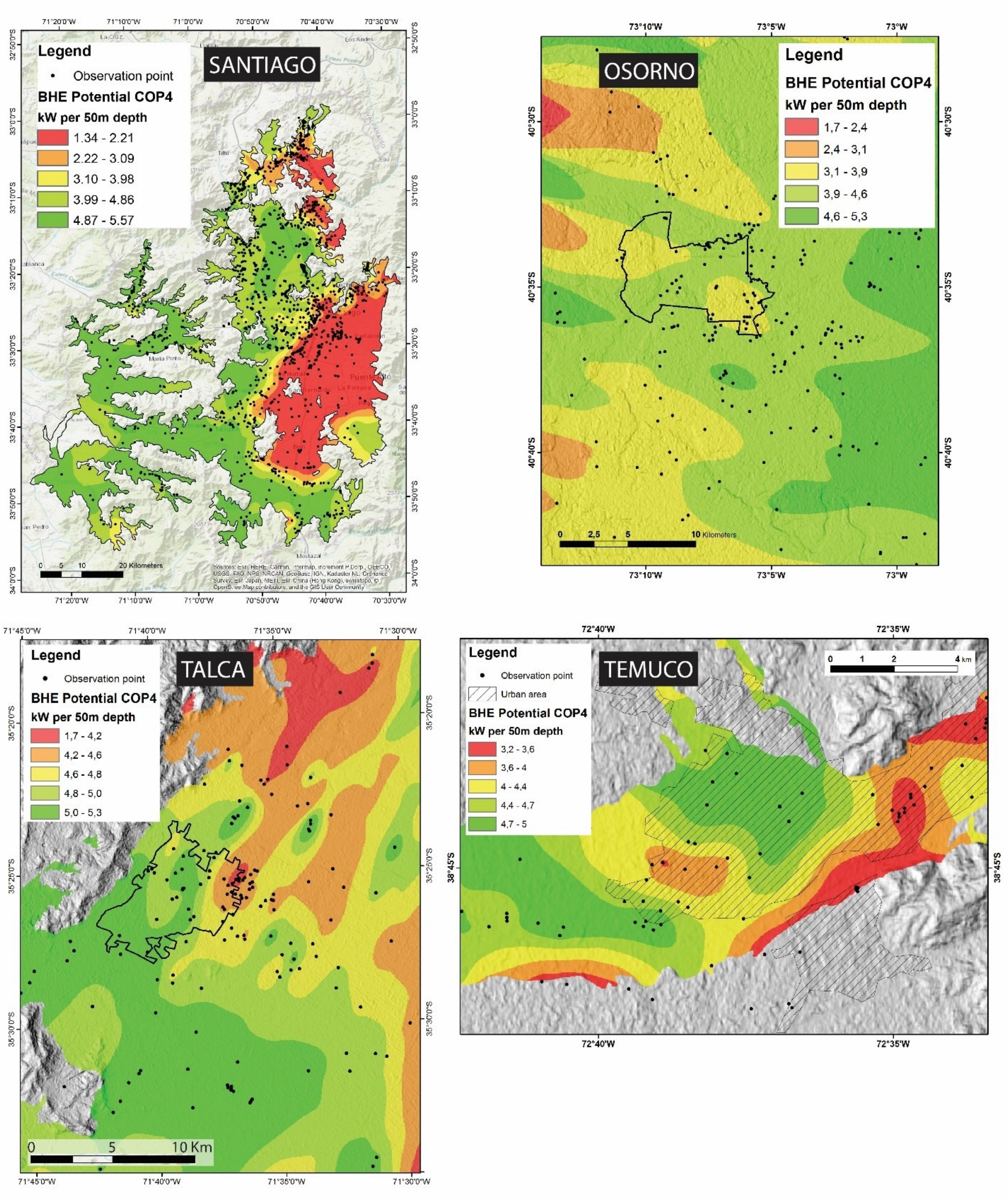

Figure 3: Available energy for BHE systems if a 50m depth well is considered in Santiago, Talca, Osorno and Temuco.

Environmental problems associated with wood combustion for space heating are a public issue where there is no unique solution. In this context, many alternatives can operate together to lessen the combustion of wood, pellet and petroleum as heat sources in domestic and industrial activities. We suggest that geothermal heat pumps can play a key role due to their zero particle material emissions. In addition, electricity generation in Chile is quickly progressing towards local, clean and renewable energies such as solar, wind and, of course, geothermal.

5. CONCLUSIONS

Given the high hydraulic gradient and groundwater recharge present in the basins of south-central Chile, there is great potential for the use of this resource for GWHP systems. Although variability exists in some parameters, the values measured in this study suggest that the heat transfer processes between the ground and the collectors (open or closed), are enhanced due to groundwater presence.

The efficiency expected for GWHP and BHE would allow to replace wood heating by a much cleaner solution, helping to mitigate air pollution in all the prospected areas.

The inclusion of geothermal pump systems in the space heating markets of polluted cities in Chile is a sustainable solution to improve the air quality. Despite the fact that the cost of this technology is well above the range of the average citizen, we establish that in a future scenario where the need for clean methods of space heating is a requirement, geothermal heat pumps must play an important role. The efficiency rate and the zero local emissions of particle material cannot be ignored based on the price of this equipment. The need for public funding and subsidy for the inclusion of geothermal heat pumps in public buildings arises as a necessary step towards widespread adoption.

In this context, Chile if favored by its geological conditions and the plan to be a coal-free country by 2050. The policies that are going to be adopted would invariably benefit the possibility of including new and efficient technology to domestic and industrial sectors. Considering this, it is of high importance that the feasibility and functioning of this machinery is fully proven in different projects along the country.

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