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Estimating low-enthalpy geothermal energy potential for district heating in Santiago basin–Chile (33.5 °S)

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A B S T R A C T

This work presents the results of a regional-scale estimation of low-enthalpy geothermal resources for district heating in the Santiago basin. The purpose of this work is to identify promising areas for the development of this type of renewable energy. The estimation was based on comparison of soil thermal properties and hydrogeological parameters, using Geographic Information System (GIS). To determine the geothermal potential, Ground Source Heat Exchanger (GSHE) coupled with heat pump was used to supply a fixed demand equivalent to the energy required to heat a Chilean standard house. The main barrier for the implementation of a GSHE coupled with heat pump is the well drilling cost, therefore the potential is presented as meters to be drilled in order to install 2 types of GSHE: 1) Borehole Heat Exchanger (BHE) and 2) Groundwater Heat Exchanger (GWHE). To assess the BHE, we used specific Heat Extraction (sHE) of sediments. To evaluate a GWHE, we used depth of groundwater table and groundwater drawdown caused by pumping water to the heat pump. The depth to be drilled ranges from 35 to 105 m in case of the BHE, while in case of the GWHE it ranges from 10 to 400 m.

1. Introduction

The soil naturally stores atmospheric heat in addition to the heat flow coming up towards the ground from the basement rock. Because of the low thermal conductivity of the soil, temperature is not subject to daily and seasonal atmosphere variations at moderate depths, remaining almost constant throughout the year at depths less than 15 m [*e.g.* Ref. [1]]. Thermal energy stored in the ground can be extracted using a Ground Source Heat Exchanger (GSHE) that uses the heat stored in ground and groundwater to increases the efficiency of a heat pump that supplements the energy needed for heating or cooling a space [2].

GSHE coupled with heat pump is a widespread type of acclimatization system, because it can be used for heating or cooling and can be developed anywhere and anytime with a very low environmental impact [3]. By 2010, GSHE coupled with a heat pump accounted for 68.3% and 47.2% of the worldwide capacity and usage of direct uses of geothermal energy, respectively. The installed capacity was 33,134 MWt and the annual energy usage was 200,149 TJ/yr, with a capacity factor of 0.19 for heating [4].

In order to evaluate the favorability for installing GSHE coupled with heat pump in Santiago basin for heating purposes, a number of maps were prepared to identify promising areas for the development of this type of acclimatization. Two different types of GSHE were considered for this purpose, a closed system, hereafter called Borehole Heat Exchanger (BHE), and an open system, hereafter called Groundwater Heat Exchanger (GWHE). BHE is the most common type of GSHE, which consist of a U-shape pipe, usually made of high-density polyethylene, which are inserted in vertical boreholes. A fluid, generally water or sometimes with antifreeze, circulates through the pipe exchanging heat with the ground [2,3]. Depth of the BHE depends on thermal properties and water content of the soil and velocity of the groundwater flow. To heat a house with a BHE, its depth generally ranges between tens to few hundreds of meters [*e.g.* Refs. [5,6]]. GWHE is another common type of GSHE, which consist of extracting groundwater to exchange heat

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between the groundwater and the heat pump. The extracted water can be used or re-injected into the aquifer [2,3]. The depth of GWHE depends on groundwater table depth, its variability with time and the drawdown depth of the extraction well, which depends on the pumping rate of groundwater. A case study with detailed evaluation of a GWHE was presented by Ref. [7].

In Chile, use of GSHE coupled with a heat pump is very limited due to the lack of information about the advantages offered by these systems and their high initial cost due to drilling. High drilling cost may be due to an oversized design of the GSHE, because lack of reliable subsurface information.

The present work aims at finding the promising areas in the Santiago basin for the implementation of direct use of low-enthalpy geothermal energy for heating purposes, using stratigraphy and groundwater data. It will finally delimitate those areas where direct use of low-enthalpy geothermal energy could be an environment friendly choice heating systems.

2. Study area and geological context

The study area is Santiago basin of the Metropolitan Region in central Chile, which has more than 6.5 million inhabitants that represent *ca.* 40% of Chilean population (XVIII Chilean Census, 2012). Santiago basin is located between the Main Andean Range and Coastal Range (Fig. 1). According to [8], based on [9] classification, climate of Santiago is Subtropical Tempered with Dry and Warm Summer. The annual mean temperature is 13.6 °C ranging from 0 °C in winter to 34 °C in summer [10]. The average annual rainfall is about 300 mm per year, concentrated mainly from May to August.

The Coastal Range (Cordillera de la Costa) is located west of the Santiago basin and is composed mainly by Cretaceous volcanic rocks and Jurassic to Cretaceous intrusive rocks [11–13]. Main Andean Range (Cordillera Principal) located east of Santiago basin corresponds mainly to Eocene to Miocene volcanic rocks and Miocene to Oligocene intrusive rocks [14,12,15,13].

The main active fault system in the basin is the reverse west verging San Ramón Fault System, which is responsible for the uplift along its hanging wall, Main Andean Range, with respect to the Santiago basin [16,17]. Close to the trace of this fault system, there are warm springs, with discharge temperatures ranging from 20 to 30 °C (Fig. 1). In addition, there are also some faults in the center of the basin interpreted as normal faults, which have been inverted [18,19]. There are also normal faults oriented northeast and northwest, in the Coastal Range [20,21].

3. Methodology

In order to find the most suitable areas for district heating by the direct use of low-enthalpy geothermal energy, performance of a Ground Source Heat Exchanger (GSHE) to supply a fixed energy demand of 2.7 kW was assessed in the Santiago basin. This energy demand (2.7 kW) is equivalent to the energy required to heat a Chilean standard one-story house of 50–71 m^2 with appropriate thermal insulation [22]. Performance of GSHE depends on the soil thermal properties and physical hydrogeological parameters that

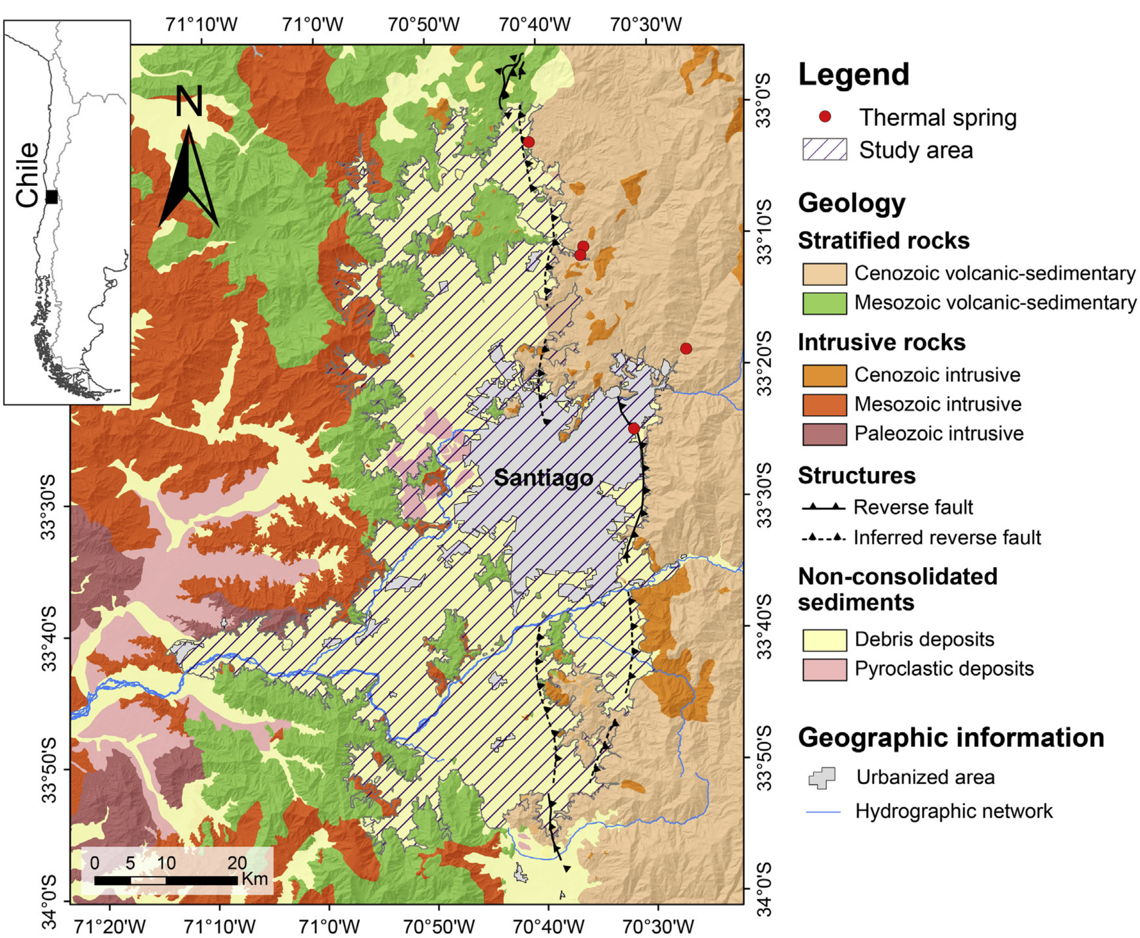

Fig. 1. Location and geological context of the Santiago basin in Central Chile.

have been used in a geodatabase to be managed and analyzed in a Geographic Information System (GIS). A statistical analysis of the database was performed with ordinary kriging of the geostatistical module of ArcMap. The ordinary kriging algorithm was used, because it optimizes the interpolation dividing the spatial variation into three components: deterministic variation, spatially autocorrelation and uncorrelated noise. In addition the ordinary kriging algorithm give the best fit and generate a continuous surface with the best fit in related estimations, as for example groundwater table estimations [23].

This work considered just one borehole in the case of BHE and two in the case of GWHE; however, for higher energy demand, it is necessary to evaluate several boreholes and their distribution [*e.g.* Ref. [24]]. Another consideration omitted in this work because of the scale is the thermally affected zone, which depends of the amount of heat exchanged and groundwater flow velocity [*e.g.* Refs. [25,26]].

3.1. Database and context

3.1.1. Sedimentary infill

Santiago basin sedimentary infill was defined based on 785 groundwater borehole descriptions. Data sources were: i) 67 borehole descriptions by the Centre of Research, Development and Innovation of Structures and Materials (IDIEM, Universidad de Chile), ii) 56 reports compiled from Rural Drinking Water Services, iii) 500 borehole descriptions from a Millennium Science Initiative (Iniciativa Científica Milenio, ISCM) project on seismotectonics and seismic hazard of the Universidad de Chile, and iv) 368 of borehole with stratigraphic information from the Directorate General of Water (Dirección General de Aguas, DGA). The borehole descriptions were complemented with morphological features (Fig. 2). The sedimentary facies are mainly alluvial and fluvial, but there are also colluvial and lacustrine facies of lesser areal extension and poorly consolidated volcanic pyroclastic sediments of Pleistocene age [12,13].

In the central and southern portions of the basin, there are alluvial fans, which correspond to high-energy depositional environments. These alluvial fans originated in the Main Andean Range and exhibit a decreasing grain-size trend towards west. In the northern and southwestern parts of the basin, there are relatively lower-energy alluvial fans. The main difference between these alluvial fans is the fine sediment content of the matrix.

Close to Mapocho and Maipo riverbeds there are fluvial deposits, with depositional energy decreasing westward. In the basin margins, there are colluvial and debris flows deposits at the foothills. There are lacustrine deposits located in the northwestern and southwestern zones of the basin. Finally, pyroclastic ash and pumice deposits, which could be reworked in some cases outcrop in the western and southwestern parts of the basin [12,13].

3.1.2. Static level of groundwater and piezometric elevation

The groundwater table was determined interpolating more than 2000 control points with the information for the last 5 decades, using a circular model, with anisotropy of ordinary kriging interpolation tool with the Geostatistical tool of ArcMap. Root-mean-square (RMS) deviation for the interpolated surface respect to control points was 10 m. Based on the lower RMS, considering a

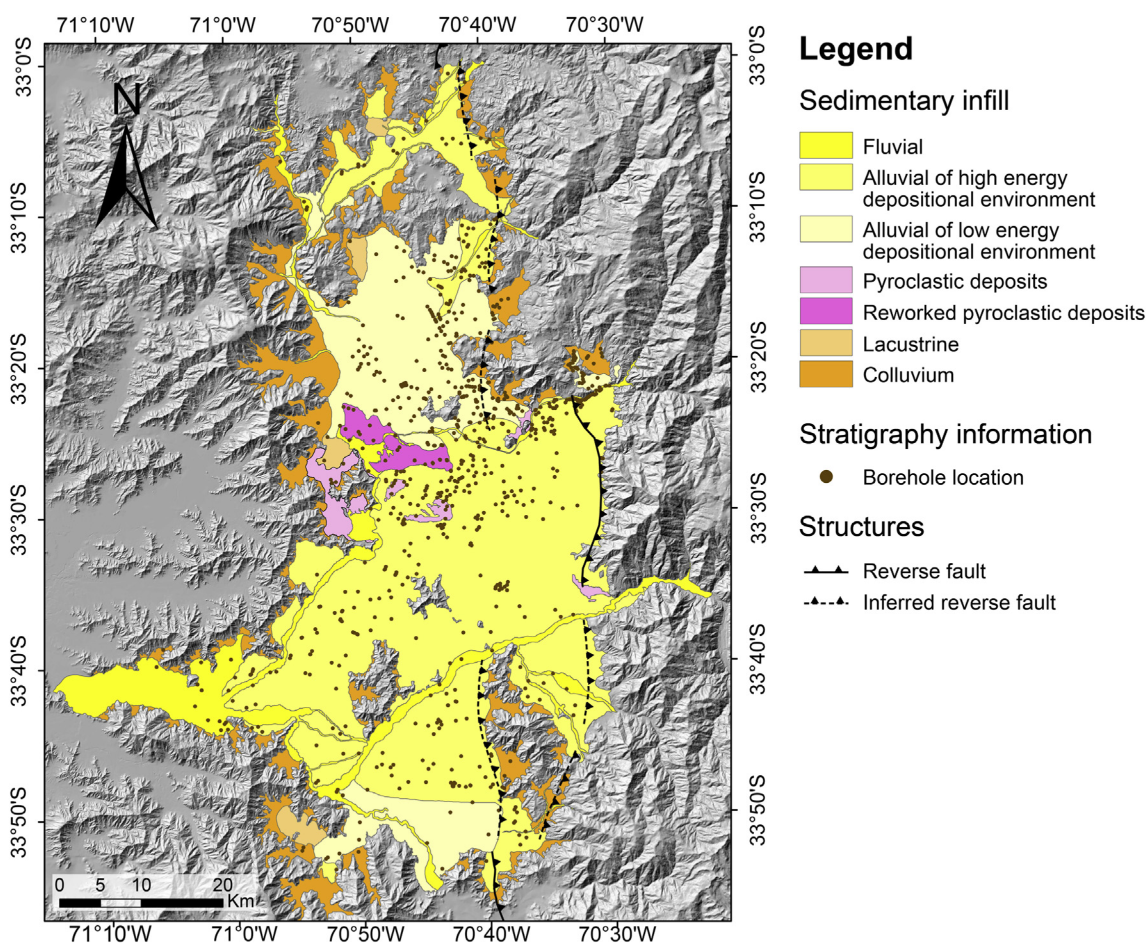

Fig. 2. Santiago basin sedimentary infill distribution (Modified of [17,27–29]).

Table 1
Typical values of specific heat extraction for sediments [36].

Soil type	Specific heat extraction (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

database ranging the last 5 decades, we propose that these little changes are due to the following: a) Water supply to Santiago city is mainly the Andean rivers, and b) the agricultural development is moderate in the region, and also in this case, the main source of water are the river, lakes and ponds. Data sources are the following: a) 31 control points from the work of [30], b) 277 reports available in the Directorate General of Water (Dirección General de Aguas, DGA), c) 1521 control points from the work of [31] on Maipo and Mapocho rivers basins, d) 103 control points of the DGA hydro-meteorological and water quality monitoring net, and e) 69 static levels measured during this work. To consider the effect of low recharge and maximum extraction of groundwater in the aquifer, the maximum static level depth for each control point was considered. Piezometric elevations were estimated by subtracting the static level by the topographic elevation.

3.1.3. Velocity of groundwater flow

The groundwater velocity was calculated from Darcy's Law as follows,

$$V_{\text{Darcy}} = \lambda \cdot i \quad (1)$$

Here λ is hydraulic conductivity and i is hydraulic gradient. Hydraulic conductivity values were obtained from Ref. [32], whereas hydraulic gradient was estimated as the slope of the piezometric elevation surface.

3.1.4. Groundwater temperature

Considering a heat pump operating at maximum theoretical efficiency for heating purposes (*i.e.*, Carnot Cycle), the coefficient of performance (COP) can be expressed as [33].

$$\text{COP}_{\text{max}} = \frac{\theta_h}{\theta_h - \theta_c} \quad (2)$$

The efficiency of a heat pump depends on several factors, especially the difference between the output temperature of the heat pump (hot temperature θ_h) and input temperature (cold aquifer temperature θ_c). Although the maximal theoretical efficiency is not achievable by real systems, it can be used as an indicator of efficiency. From the equation (2), it can be deduced that for a fixed hot temperature θ_h , the input temperature θ_c will determine

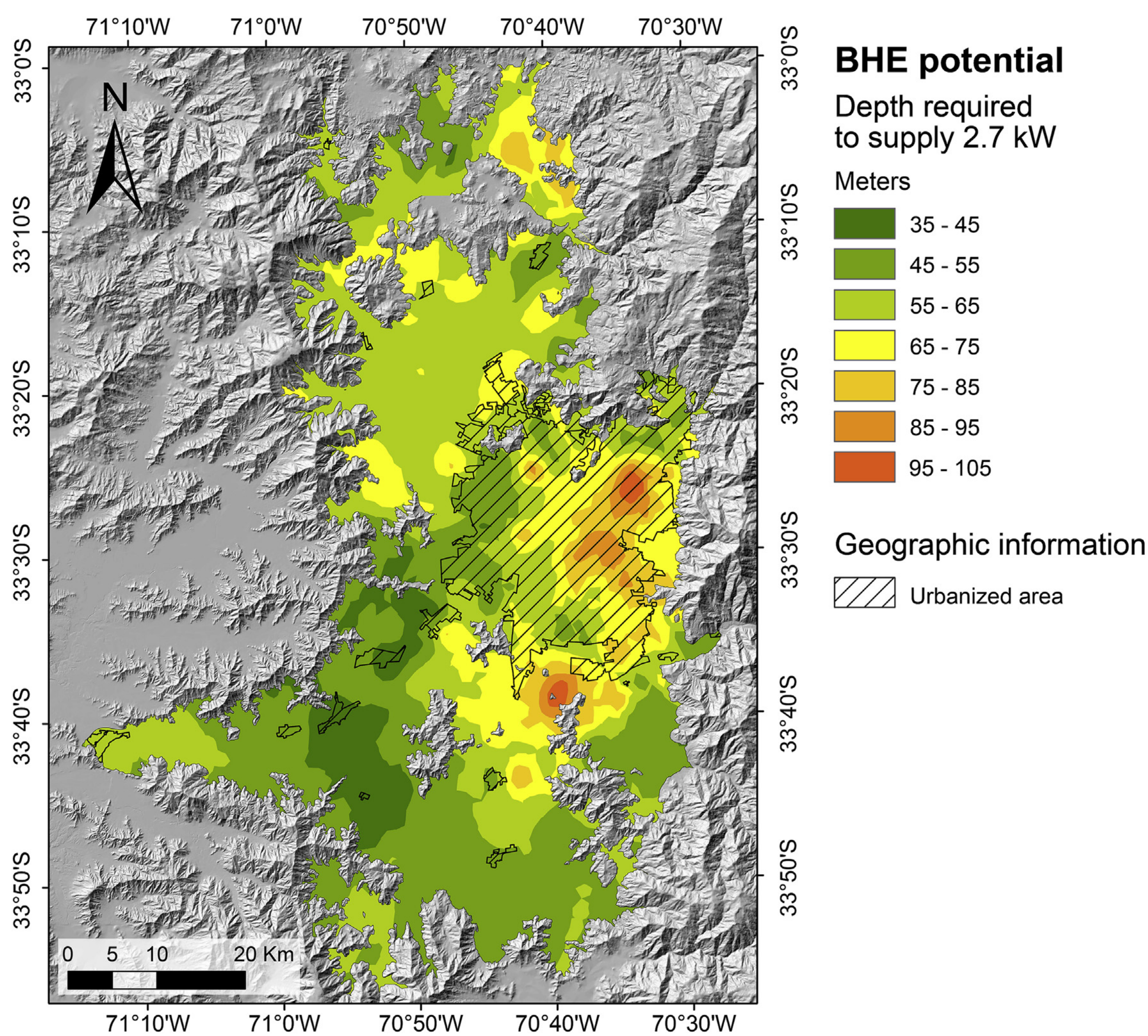

Fig. 3. Drilling depth required to supply an energy demand of 2.7 kW, using a BHE in the Santiago basin.

the efficiency of the system. Higher θ_c implicate better heat pump performance.

Several studies indicate that higher input temperatures will increase the efficiency of the heat pump on heating mode [*e.g.* Ref. [34,35]]. For this reason, a groundwater temperature distribution map can be a qualitative indicator of the efficiency of the GSHE coupled with a heat pump. Precisely, the zones with higher groundwater temperatures will have better performance than those with lower groundwater temperatures.

Groundwater temperature was measured in boreholes, and thermal springs. In places where we could deploy a thermometer into the well, the temperature was measured inside the wells.

3.2. Ground Source Heat Exchanger (GSHE)

In order to assess the meters to be drilled for heating a building with a BHE we used the methodology proposed by Ref. [5], based on specific Heat Extraction (sHE) of different types of sediments. This methodology was applied for each borehole with stratigraphic information dividing the well stratigraphy in a dry upper unit and a saturated lower unit. The assessment of the meters to be drilled for heating a building with a GWHE is proposed by this work based on the depth of the groundwater table and the expected drawdown for the pumping well.

3.2.1. Borehole Heat Exchanger (BHE)

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 Ref. [5] as the specific Heat Extraction (sHE) in units of Watts per meter (W/m). The sHE values were defined according to the [36] (Table 1), whose values are based on 2400 operating hours [5]. The Santiago basin borehole descriptions were re–classified according to [36] soil type to apply these sHE values consistently.

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

$$sHE_d = \frac{1}{Th_d}\sum_{i=1}^{k}(sHE_i \cdot Th_i) \quad \text{if} \quad \sum Th_i < \text{groundwater table} \qquad (3)$$

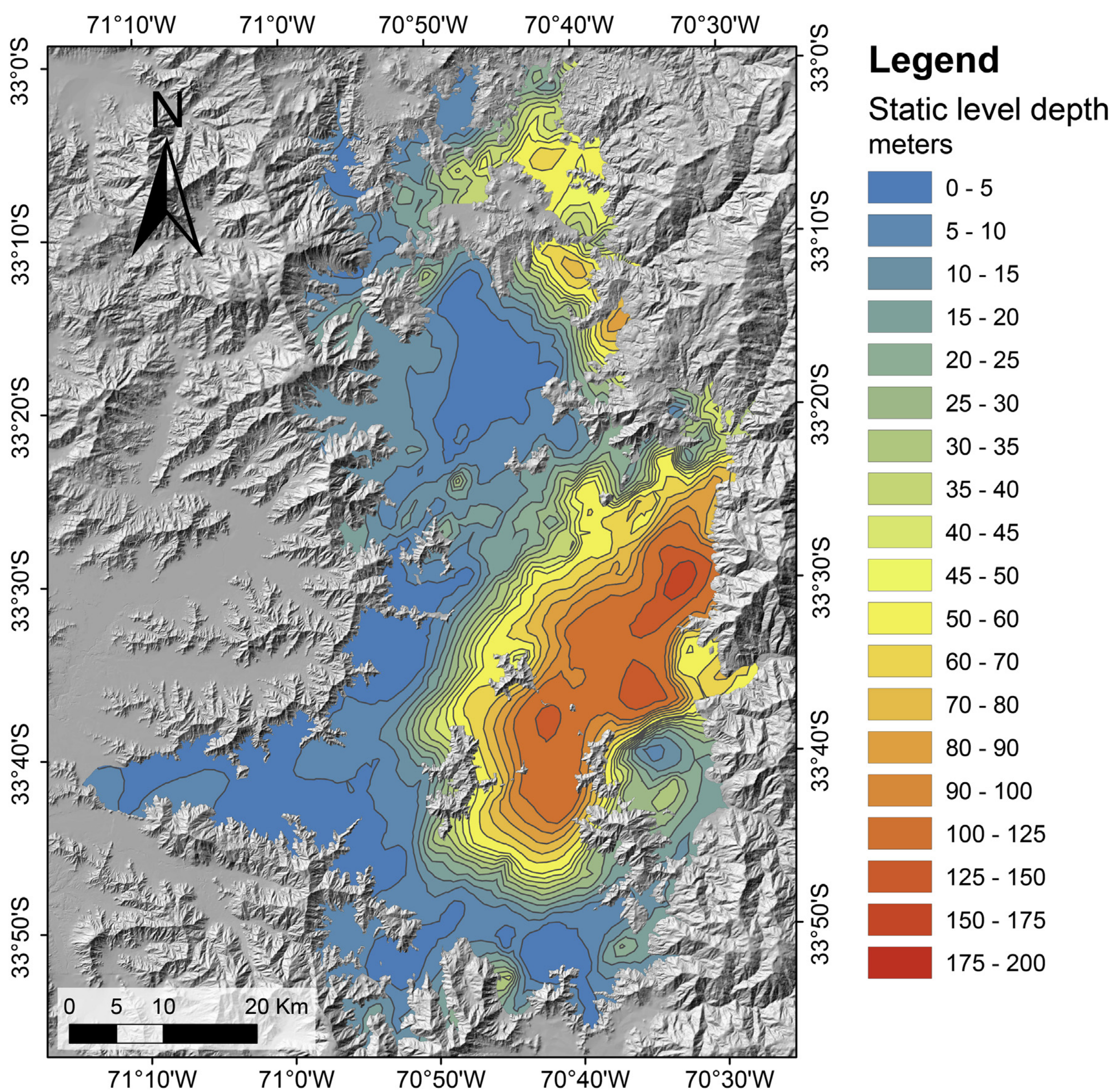

Fig. 4. Static level depth in the Santiago basin.

$$sHE_s = \frac{1}{Th_s}\sum_{i=k+1}^{n}(sHE_i \cdot Th_i) \quad \text{if} \quad \sum Th_i \geq \text{groundwater table} \tag{4}$$

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. Then the meters to be drilled for a BHE implementation in each borehole with sedimentary information is calculated as follows.

$$Th = \frac{P}{sHE_d} \quad \text{if not neccesary to reach saturated layers} \tag{5}$$

$$Th = Th_d + \frac{P - (sHE_d \cdot Th_d)}{sHE_s} \quad \text{if is neccesary to reach saturated layers} \tag{6}$$

Here Th corresponds to the meters to be drilled to supply a fixed energy demand (P) and Th_d is dry thickness in equation (6).

3.2.2. Groundwater Heat Exchanger (GWHE)

Operation of a GWHE consists of extracting groundwater to exchange heat between the extracted groundwater in the heat pump. Afterward the water is re-injected into the aquifer. To assess the depth in meters to be drilled in order to heat a building with a GWHE, the following factors were considered: 1) depth of the static levels twice, one for extraction well and the other for the reinjection well, and 2) drawdown depth caused by pumping of water. Then the depth in meters to be drilled for the implementation of a GWHE was calculated as follows.

$$GWHE_{Depth} = 2 \cdot (\text{static level depth}) + \text{groundwater drawdown} \tag{7}$$

Drawdown depends mainly on the pumping rate and hydraulic properties of the porous media. An approach derived by Ref. [37] from the Logan equation, for the drawdown is calculated as follows,

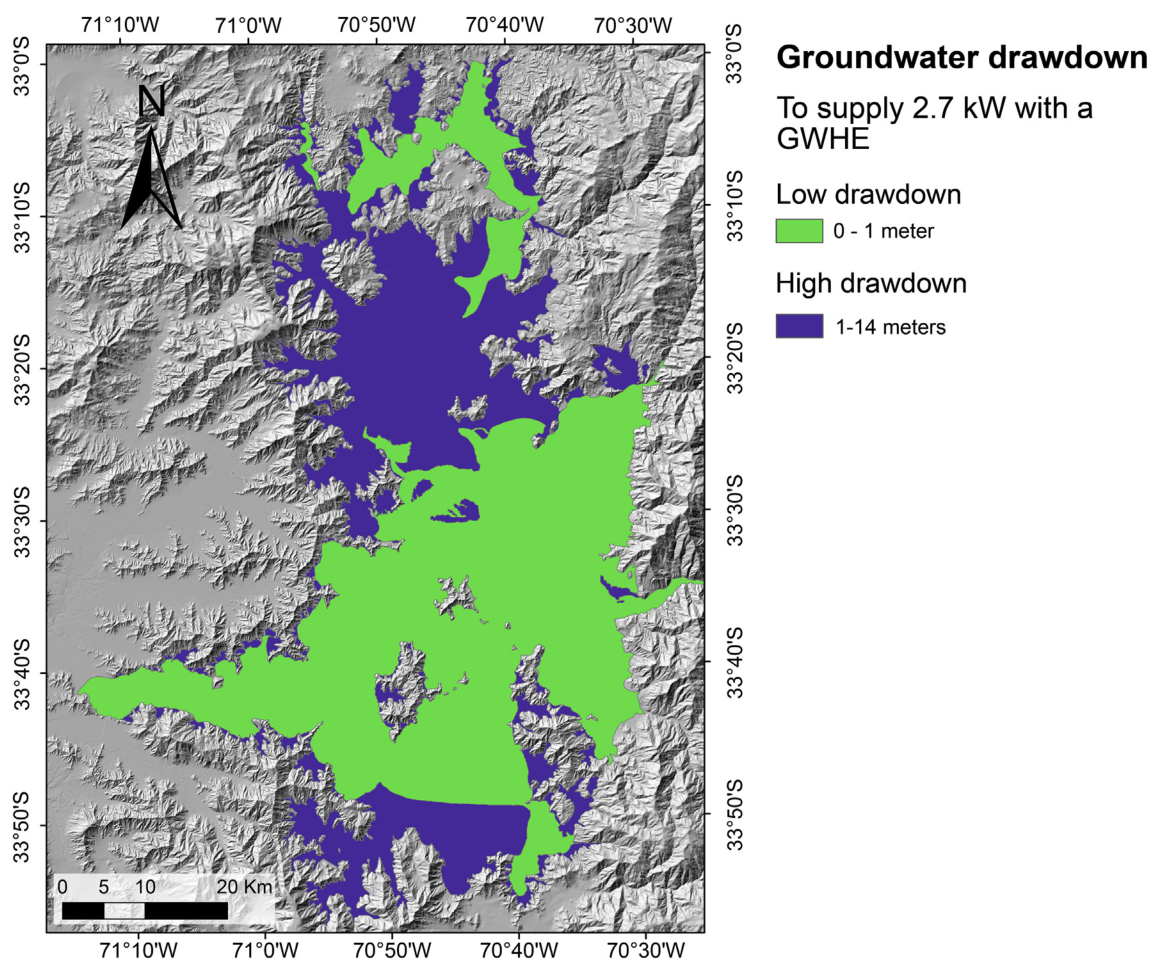

Fig. 5. Estimation of drawdown by pumping rate of groundwater to supply 2.7 kW with a GWHE.

$$T = 2 \cdot \frac{Q}{S_w} \tag{8}$$

In the above equation T is transmissivity (m^2/s), Q is pumping rate (m^3/s) and S_w is the drawdown (m). Although this equation is valid for a confined aquifer, it could be used in the case of an unconfined thick aquifer as in Santiago sedimentary basin [38]. As hydraulic conductivity is transmissivity per saturated thickness, equation (8) could be rewritten as follows.

$$S_w = 2 \cdot \frac{Q}{\lambda \cdot b_e} \tag{9}$$

Here λ is hydraulic conductivity (m/s) and b_e is saturated thickness (m). Considering saturated thickness is the maximum drawdown as an approximation, equation (9) could be rewritten as follows,

$$S_w = \sqrt{\frac{2Q}{\lambda}} \tag{10}$$

The pumping rate required to meet the energy demand using GWHE depends on the energy demand, physical properties of water and the difference between the inlet and outlet groundwater temperatures in the heat pump.

$$Q = \frac{P}{\rho \, c_P \Delta T} \tag{11}$$

In the above equation Q is pumping rate (m^3/s), P is the energy demand (J/s), ρ is water density (kg/m^3), c_P is the specific heat capacity of water at constant pressure (J/kgK) and ΔT is the difference between the inlet and outlet groundwater temperatures (°C).

4. Results

4.1. Depth to be drilled for the implementation of a BHE

The depth to be drilled to supply a fixed energy demand of 2.7 kW (energy required for heating a Chilean standard house as described earlier) with a BHE, was estimated for each borehole, where stratigraphic information was available. A continuous surface using these results was estimated by interpolation using the ordinary kriging method with the geostatistical tool of ArcMap. The best estimation was considering a circular model with anisotropy that provided less than 5 m of estimated error (Fig. 3).

The drilling depths are in the range between 35 and 105 m, with an average value of 58 m. The southwestern sector of the basin is the most favorable part, where it is necessary to drill less than 50 m,

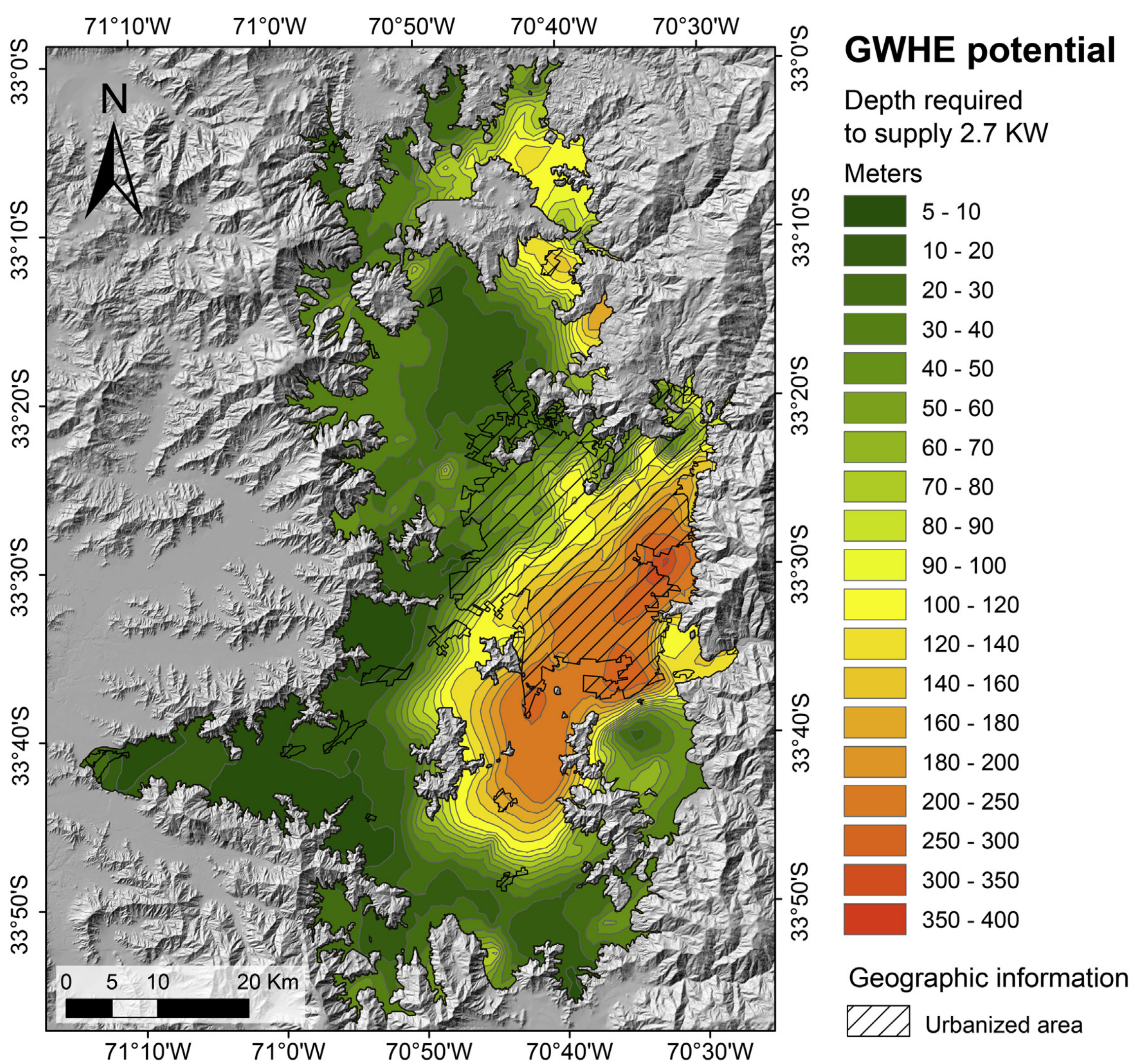

Fig. 6. Drilling depth required to supply the energy demand of 2.7 kW, using a GWHE in the Santiago basin. The depth scale is not lineal.

whereas the central eastern area of the basin is less favorable, where it is necessary to drill more than 80 m.

The main factors which control the favorability for the implementation of a BHE are the static level depth and groundwater flow velocity. The velocity of groundwater flow is highly dependent on the hydraulic conductivity, which in Santiago basin sedimentary infill is higher for fluvial and alluvial facies which are high-energy depositional environment.

There are areas where despite having a shallow static level are not part of the most favorable areas for the development of BHE, because of the low hydraulic conductivity. These areas correspond to low-energy alluvial fans, lacustrine, and pyroclastic deposits.

4.2. Depth to be drilled for the implementation of a GWHE

The depth to be drilled to supply a fixed energy demand of 2.7 kW (energy required for heating a Chilean standard house as described earlier) with a GWHE was also estimated based on static level depth and groundwater drawdown. Because of the static level depth variation through time, the maximum value was considered in each control point. A continuous surface which represents static level depth was estimated by interpolation using ordinary kriging, considering a circular model with anisotropy with the geostatistical tool of ArcMap (Fig. 4).

For the estimation of the groundwater drawdown, required pumping rate to meet the energy demand is necessary. This pumping rate was estimated for each control point that reaches the static level depth according to equation (11). The parameters required were energy demand of 2.7 kW, water density 1000 kg/m^3 and specific heat capacity of water at constant pressure of 4.183 J/kgK at 20 °C. Because of the low-energy demand, and therefore low caudal expected for heating a Chilean standard house [22], the difference between the inlet and outlet groundwater temperatures in the heat pump was not considered as a driving factor and it was assumed equal to 5 °C. In case of a higher energy demand this temperature difference should be evaluated in detail in the design stage.

Drawdown was estimated based on equation (10). Hydraulic conductivity values used for the estimation are from Ref. [32] and it was assigned according to the type of sediment just below the static level. Because hydraulic conductivity is extremely variable and higher drawdown in fine-grained sediments, the layers composed of fine-grain sediments were considered only when thickness was greater than 10 m. As variations in hydraulic conductivity are in orders of magnitude, the estimated drawdown has a bimodal distribution composed of coarse-grained sediments and fine-grained sediments. Based on this bimodal distribution two surfaces were created, one considering only coarse-grained sediments, which produces lower drawdown values and another for fine-grained

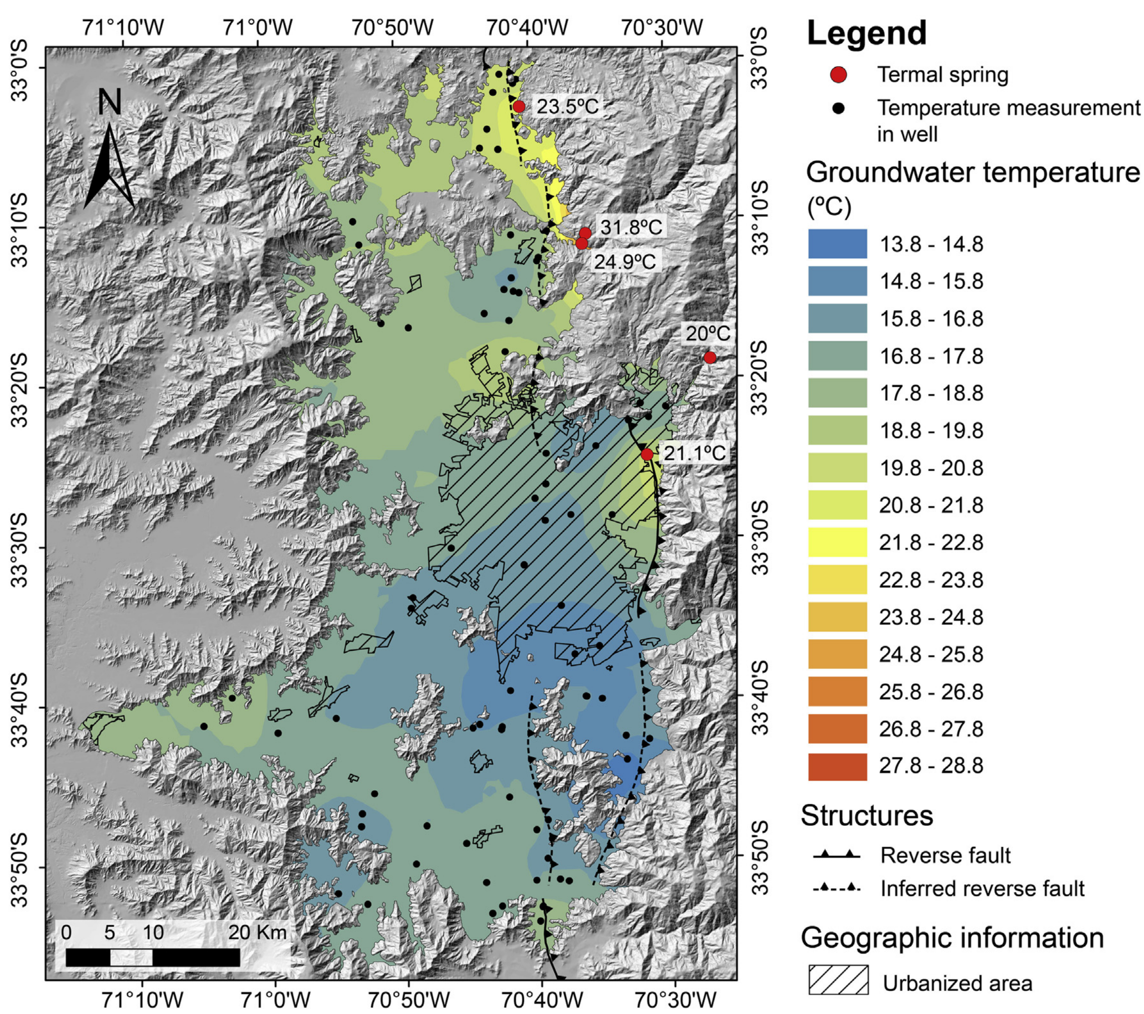

Fig. 7. Groundwater temperature distribution in Santiago basin.

sediments, which produce higher drawdown values (Fig. 5). The drawdown surface was according to the basins sedimentary infill distribution (Fig. 2).

Finally the depth to be drilled to supply a fixed energy demand of 2.7 kW with a GWHE, was estimated for each borehole with stratigraphic information which reaches the groundwater according to equation (7). A continuous surface using these results was drawn by interpolating individual estimations, using a circular model with anisotropy of the ordinary kriging interpolation tool in the Geostatistical module of ArcMap (Fig. 6).

The depth to be drilled ranges from 5 to 400 m, with an average value of 68 m. The most favorable areas for the development of GSHE are the northern, western and southern part of the basin, where the drilling depth is less than 30 m. Higher drawdown produces less favorability in areas with fine-grain sediments. In case of an energy demand higher than the required for heating a Chilean standard house, a detailed evaluation of drawdown in the pumping well of the GWHE must be necessary, especially in those places where the sedimentary infill is composed of poor hydraulic conductivity sediments.

5. Discussion

As mentioned in the Section 3.1.4, the groundwater temperature distribution can be used as qualitative indicator of the GSHE performance for heating purposes. For Santiago basin, the distribution of groundwater temperature was estimated by interpolating 82 temperature measurements in the drinking water wells and 5 temperature measurements in thermal springs located at the eastern edge of the Santiago basin. The data were determined using a circular model with anisotropy of ordinary kriging interpolation tool in the geostatistical module of ArcMap (Fig. 7). Groundwater temperature ranges between 13.8 to 19.0 °C for the drinking water wells and from 20.0 to 31.8 °C for thermal springs. The average groundwater temperature for the basin is 17.4 °C.

As shown in Fig. 7, higher groundwater temperatures areas (yellow (in the web version)) will have better performance of GSHE compared with lower temperatures zones (blue (in the web version)). Those areas next to natural thermal springs (red (in the web version) dots) are the best places in terms of performance of Groundwater Heat Exchangers, because groundwater reaches the surface naturally and its temperature ranges between 20 to 31.8 °C, which increase the efficiency of the GSHE for heating purposes.

6. Conclusion

This work presents a regional evaluation of a GSHE as an alternative for heating a standard Chilean house using geological and hydrological parameters. It is expected that mapped favorable areas will be promising for heating bigger buildings or other direct usages of low-enthalpy geothermal energy.

The depth to be drilled in case of the BHE ranges from 35 to 105 m with an average of 58 m. In case of the GWHE, the depth to be drilled ranges between 10 and 400 m, with an average value of 68 m. Considering the most favorable areas for development of GSHE for heating a house, the suitable areas for GWHE are the better than those for BHE. GWHE is preferred in case of shallow groundwater table, and BHE is preferred in case of deep groundwater table.

The main factor, which controls the favorability of GSHE in Santiago basin, is the static level depth. For BHE the depth of static level is important because of the higher thermal conductivity of saturated sediments. In the case of GWHE, the groundwater is the heat source. For these reasons, zones with shallow groundwater levels are favorable for the installation of both types of systems. Another important factor is the hydraulic conductivity of saturated layers, because in the case of BHE, it improves the efficiency of the thermal heat exchanges due to groundwater flow and in the case of GWHE, it reduces the drawdown magnitude.

The variation of the depth in meters to be drilled for the installation of a BHE is less than those for the installation of a GWHE, because in the case of GWHE, it is necessary to reach the static level depth, which is highly variable in Santiago basin.

Thermal springs are favorable areas for heating purposes, because the groundwater reaches the surface naturally with temperature ranges between 20 to 31.8 °C, which increase the efficiency of heat pumps.

Acknowledgments

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