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ScienceDirect

Energy Procedia 158 (2019) 6099–6104

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Spatial Data Assisted Ground Source Heat Pump Potential Analysis in China, a Case of Qingdao City

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Abstract

Nowadays, China faces challenges of further implementing heat pump technology for meeting building heating and cooling demand. The utilization of heat pumps, especially ground source heat pump (GSHP) is associated with a number of geological, hydrological as well as meteorological criteria. Thus it is essential to systematically address the feasibility of ground source heat pumps application using quantitative evaluation. Spatial data analysis is a method widely used in energy field to investigate renewable energy potential. Therefore, this study strives to provide an estimation of electricity driven GSHP's potential in north China using spatial data assisted tools. Followed by a case study using the methodology recommended, a spatial data assisted GSHP potential evaluation model is built for Qingdao city in north China. The evaluation model is constructed and analyzed through spatial data processing software visualized by ground source heat pump potential maps. The result maps show that, places with most potential of GSHP application locate in south Qingdao close to the sea. Such places have a higher ground extractable heat and relatively low drilling cost.

Keywords: spatial data analysis; ground source heat pump; China

1. Introduction

Heat pumps is regarded as a renewable energy technology in China, and it is mainly used in building sector. GSHP has been widely used in countries such as the US, UK, Sweden and Japan [1]. China is also in rich of shallow

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1876-6102
10.1016/j.egypro.2019.01.504

earth heat energy, suitable for heat pump technology application [2]. Since energy demand from the building sector in China is mostly covered by fossil fuel, in order to achieve a sustainable building space heating goal, China's Ministry of Housing and Urban-Rural Development (MOHURD) and Ministry of Finance (MOF) had promulgated a series of policy decisions to encourage the application of GSHP. Despite many demonstration projects had been established during the past decade, GSHPs are still facing challenges in technology application as well economic competitiveness. Whether electricity driven GSHP is the most environmental friendly room heating technology in China also needs further investigation due to the fact that electricity generation in China is heavily coal based. Among all the questions that should to be answered, finding the geographical locations with best GSHP application potential is a prioritized issue. Thus, a spatial analysis assisted GSHP potential evaluation methodology is recommended in this study to identify GSHP application potential for large scale territory evaluation.

In real life, all events happen somewhere at some time [3]. Consequently, objects have spatial and temporal coordinates attached to them. Therefore, spatial analysis means the studied targets are analysed based on their spatial/geographical and sometimes temporal references. Often such analysis can be visualized on a map.

In the field of energy technology, spatial analysis is often used by researchers to predict the exploitation potential of certain kind of energy or the application potential of an energy system. For example, Viana et al. [4] assessed the potential of forestry biomass for energy use in Portugal. Fiorese and Guariso [5] used GIS method to estimate biomass potential from energy crops in Emilia-Romagna of Northern Italy. Sliz-Szkliniarz and Vogt [6] evaluated wind energy potential in Kujawsko–Pomorskie Voivodeship of Poland. Aydin et al. [7] assessed wind energy systems potential in western Turkey using GIS tools. Grassi et al. [8] developed a spatial data based approach to find wind projects potential locations and predict their economic exploitable energy in Iowa USA. Ramachandra and Shruthi [9] investigated wind energy potential in Karnataka India using GIS tools. In solar energy field, Bergamasco and Asinari mapped photovoltaic potential in north-west Italy calculating through GIS data. Gadsden et al. [10] discussed the possibility of using GIS-based approach to assist energy planners to increase solar water heater application. In geothermal energy field, Schiel et al. [11] modeled shallow geothermal energy potential for CO_2 emission mitigation in Ludwigsburg, Germany. García-Gil et al. [12] mapped low-temperature geothermal potential in Barcelona Spain using spatial data method. In general, spatial data analysis as a tool to support energy field has been widely used in all kinds of energy potential prediction.

In the model devised in this paper to evaluate GSHP potential, ground layers are treated as spatial objects that can be geo-referred, stored to spatial data tools. Such attribute data are analysed using a combination of spatial analysis techniques, such as point interpolation and raster layer calculation. The most proper areas with the highest potential for GSHP can be found based on available heat that could be extracted from underground. Ultimately, this paper intends to use spatial analysis method to construct a model for large scale evaluation of GSHP potential. It is aimed to assist policy makers decide if GSHP should be installed in a certain location for de-carbonization of building energy sector in China.

Nomenclature

BHE	borehole heat extraction, kW
SHE_k	specific heat extraction for k-th homogeneous ground layer, W/m
L_k	length of k-th homogeneous ground layer, m

2. Methodology and model setup

2.1. Spatial analysis based GSHP potential evaluation methodology

2.1.1. Defining potential and choosing model toolkit

In order to reach a reliable estimation of GSHP potential, the first step is to clarify the word potential. In this study, potential is defined as availability and profitability. Areas with high potential for implementing GSHP are those with relatively higher heat source availability. Also such areas shall benefit from social-economic and environmental profits if GSHPs are to be installed instead of alternative technologies. For large scale regional analysis as carried out in this study, geospatial data is processed using software ArcGIS. ArcGIS is powerful in offering a unique set of capabilities for applying location-based analytics. It is widely used for creating and using maps for better visualization, compiling geographic data as well as analysing spatial information.

2.1.2. Model theory and data collection

Electricity driven GSHP is a highly efficient renewable heating technology that could potentially replace traditional heating alternatives such as coal boilers or electric heaters. Two types of GSHP is often installed for space heating and cooling purposes. Closed loop GSHP extracts heat from underground soil or rock through borehole heat exchangers whereas open loop GSHP utilises ground water from underground aquifers. In this study, only closed loop GSHP is considered. Open loop GSHP is not recommended at this stage since aquifer water is under strict environmental protection in China.

In the context of closed loop GSHP, there are horizontal ground heat changers or vertical borehole heat changers to choose. For densely populated Chinese cities where land resource is limited, vertical borehole heat exchanger is recommended. In China, typical vertical borehole varies from 50 to 150 meters hosting a single or double U pipe that reaches the end of the borehole [13]. Sometimes the borehole is grouted by thermal conductive materials and water or water solution flows inside the pipes exchanging heat with surrounding soil or rock. The ability of closed-loop GSHP to utilise earth geothermal energy is associated with the number of boreholes as well as extractable heat per borehole. Therefore, it is important to obtain extractable heat value for a borehole. In order to obtain borehole heat extraction (BHE) value, it is necessary to learn about the underground composition at each borehole location. In reality, usually a thermal response test is carried out to collect on-site BHE data for each specific GSHP project. But when a large scale GSHP potential evaluation carried out for a whole city like in this study, it is impossible to perform thermal response test everywhere since it is too expensive and impractical. Some researchers use a number of borehole drilling data to generate a 3D subsurface ground model for BHE simulation such as in [14]. But in China, such borehole data is very difficult to obtain due to confidentiality issues as well as cost of drilling. In this situation, this paper proposes a simplified thickness-weighted ground layer model based on available geology information. The thickness of each homogeneous geological stratum is estimated based on administrative map, geology map and geology logbook data. Then a homogeneous ground stratum is assumed to have similar ground thermal properties.

After establishing the ground strata model, specific heat extraction value in watt per meter is assigned to each homogenous soil/rock. Typical values of specific heat extraction have been examined through on-site thermal response tests for main soil and rocks for a standard heat pump system that works for 2400 hours a year by German VDI standard, and these values are borrowed to this study [15]. They can be found in table 1.

Table 1. Specific heat extraction (SHE) values suggested by VDI

Dominant soil or rock	SHE value for 2400 hours (W/m)	SHE value applied in this study (W/m)
Gravel, sand, dry	<20	15
Gravel, sand, saturated water	55-65	55
For strong groundwater flow in gravel and sand, for individual systems	80-100	80
Clay, loam, damp	30-40	30
Limestone (massif)	45-60	45
Sandstone	55-65	55
Siliceous magmatic rock (e.g. granite, diorite)	55-70	55
Basic magmatic rock (e.g. basalt)	35-55	35
Metamorphic rocks (e.g. gneiss)	60-70	60

Since each ground layer corresponds to a specific extractable thermal energy in the unit of watt per meter, BHE is calculated by summation of specific heat extraction of each homogenous stratum. The equation used to calculate extractable heat energy of each borehole is given by:

$$BHE = \frac{1}{L}\sum_{k=1}^{n} SHE_k L_k \tag{1}$$

This methodology is illustrated by figure 1.

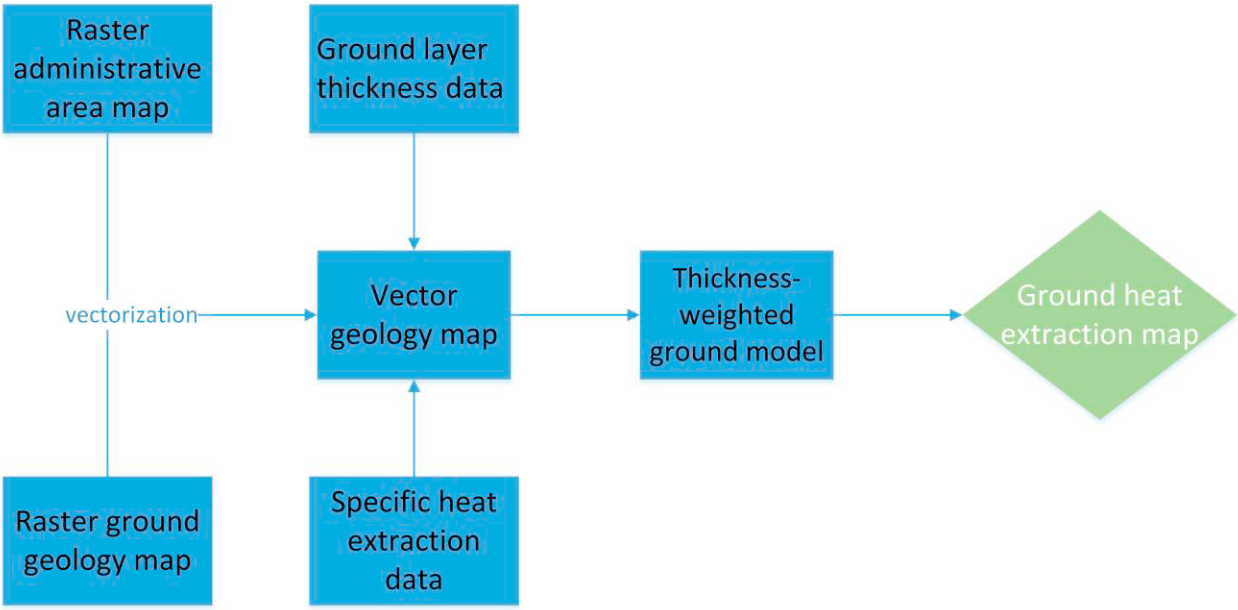

Fig. 1. Illustration of methodology flow chart

2.2. Data processing

In this study, a large amount of data is extracted from geology maps, which are in a raster form. Digitalization such data is the foundation of further processing using spatial analysis tools. Vectorization is the route used to transform raster maps into vector maps in ArcGIS. Two types of data need to undergo vectorization. One type is the polygons, lines or dots on the map that has spatial attributes. The other type is the data without spatial reference such as annotations. After having vector geology maps with administration boundaries, ground thickness layer data is retrieved from study area's geology logbook. Such logbook is either published or can be obtained from local geology authorities. Finally, SHE value is assigned to each ground layers and heat extraction value for a borehole can be calculated.

2.3. Case study area

In this study, Qingdao city is chosen to demonstrate the application of recommended methodology. Qingdao is a coastal city located in north China. It sits in the east coast of Shandong peninsula at a coordinate around 36°04'N and 120°23'E. Qingdao has a population of 9 million and an urban area of 3239 km^2. Bedrock of Qingdao is mainly magmatic and metamorphic rocks such as granite and gneiss. Quaternary layer in Qingdao is thin clay or sand of 5 meter to 10 meter. The underground water is stored in loose and porous rock such as sandrock.

In this study, for simplification, an average thickness of 7.5m Quaternary ground surface is chosen for rock dominant geological regions based on geology logbook. The major component of Quaternary surface in Qingdao is clay and silt for inner land areas and a SHE value of 20 W/m is chosen if the soil is dry. Places within major river drainage basin or close to sea shore are having a Quaternary layer composed of sand and gravel with saturated water. For such places, the value of 55 W/m is chosen based on VDI. In Qingdao, metamorphic and magmatic bedrock regions have a poor underground water flow less than $30m^3$ per day. So underground water effects on heat exchange in such geological regions are neglected.

3. Results and discussion

Based on thickness-averaged ground SHE methodology, a ground heat extraction map for 100-meter depth borehole could be generated as figure 2 displays. Places with highest extractable ground heat are identified on the map.

As figure 2 shows, from population density map (left most map) and borehole heat extraction map (middle map) three representing areas could be identified. Number 1 shows a cluster of population that lives in area of most extractable heat from the ground, which shows a good potential for GSHP application. Number 2 identifies the most densely populated areas in Qingdao, which is located at the south coastal bay area. Such places are with medium well abundant source of ground extractable heat. Number 3 shows a third cluster of population that lives with relatively low potential of ground extractable heat. When heat demand could be satisfied by BHE, such locations can be identified as high potential areas for GSHP application.

Considering economic issues, number 1 area locates on a predominant geological area of metamorphic rocks, which is relatively soft and having a lower drilling cost (casing is usually not used in China since it is too expensive). Number 2 area, however, is on hard magmatic rock (granite as shown in right most map of figure 2), which brings about more expensive drilling cost. It is worth noticing that GSHP initial cost is strongly depended on drilling cost and GSHP operating cost is strongly depended on SHE values. The third economic factor is economy of scale: the higher the population density the higher the benefit from the economy of scale would be So it can be deduced that area 1 is having more potential of GSHP application from economic perspectives due to cheaper borehole drilling cost and more dense population density.

Since area 1 has a higher borehole extractable heat and a relatively lower borehole drilling cost, it can be regarded as the places with high GSHP application potential.

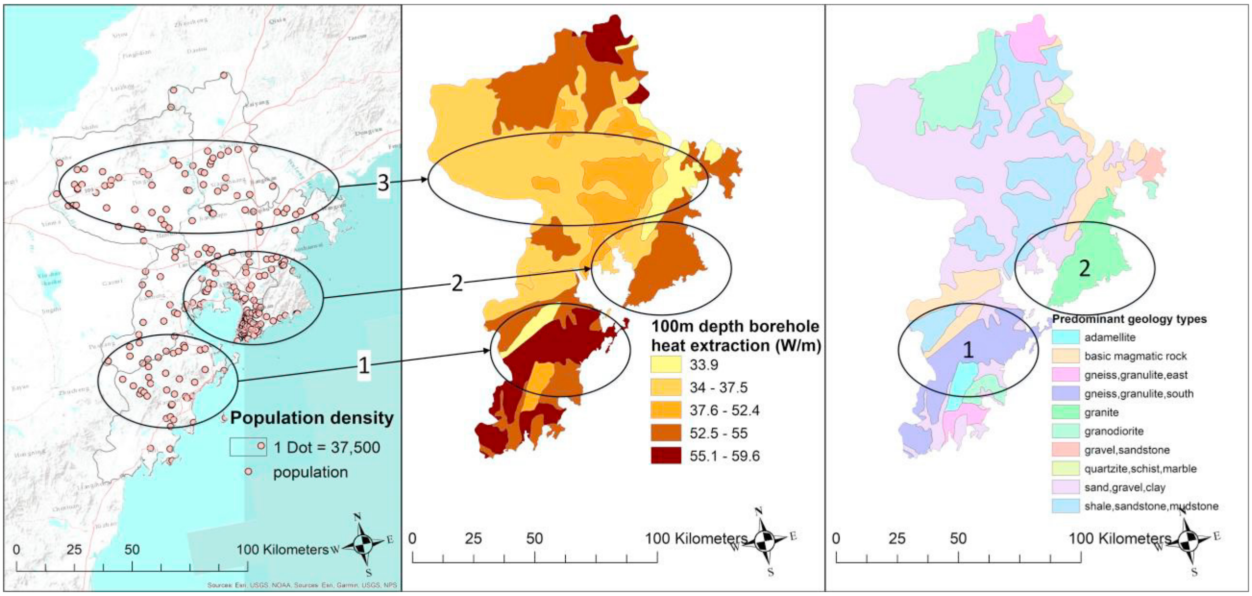

Fig. 2. Satellite population density map, borehole extraction map and geology map of Qingdao city

4. Conclusions

In this paper, a spatial data assisted GSHP potential analysis methodology is proposed. The method is described and a case study is carried out using suggested spatial analysis methodology. A spatial model is built targeting Qingdao city in north China. Result maps noticed that, for Qingdao city, the places with good potential of applying GSHP for residential buildings is located in the south of the city close to sea. Such places are densely populated and the ground extractable heat is relatively abundant. From economic point of view, places with lower drilling cost can further favor GSHP installation.

The methodology reported in this paper are reproducible for different regions in China taking local geographical and meteorological parameters into consideration, as long as required data can be accessed. Different case studies can also be carried out on various scales, such as on the entire country's level, on provincial level, on prefectural level or on urban district level. The methodology devised in this analysis can be generalized and widely used by different stakeholders in order to promote renewable energy solutions in Chinese building sector. Based on result maps, heat pump feasibility can be visualized and such maps could be utilized by policy makers for future energy planning.

Spatial analysis method suggested in this paper also provide good model flexibility. With increasing complexity of model system and improving data quality, the database can be easily maintained and expanded. Visualization is another advantage of spatial data analysis since it is easy to display research results to other experts, commercial community as well as policy makers.

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