DEVELOPMENT OF POTENTIAL MAPS FOR THE INSTALLATION OF GROUND-COUPLED HEAT PUMP SYSTEM

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ABSTRACT

Assessment of potential use of ground-coupled heat pump (GCHP) system in regional scale is necessary to promote its growth. In this study, potential maps were developed to evaluate optimum locations for the installation of GCHP system in Tsugaru Plain located in Aomori Prefecture of Japan. Development of potential maps based on local geological and hydrological information can reduce the initial cost of the system. A regional scale groundwater and heat transport model was constructed to comprehend groundwater flow system and subsurface temperature distribution of the Tsugaru Plain. From the results of 3D numerical model, thematic maps of groundwater velocity, subsurface temperature, water table depth and sand-gravel ratio were prepared in GIS. Based on these thematic maps, potential maps were prepared for air conditioning and snow melting purposes using overlay model in GIS.

Keywords: ground-coupled heat pump system, groundwater flow, heat transport, potential map, GIS

1. INTRODUCTION

Ground-coupled heat pump (GCHP) system is energy efficient and environment friendly technology that utilizes natural heat stored in subsurface of shallow depth up to 100m for air conditioning and snow melting purposes. Development rate of this system is gradually increasing (Ministry of the Environment, 2012), however the pace is still limited due to higher initial cost resulted by oversized design of ground heat exchangers and lack of information on its advantages. Evaluation of suitable locations for the installation of GCHP system considering local hydrogeological and thermal information is essential for the optimum design and consequent enhancement in its growth. With this in mind, potential maps were developed for Tsugaru Plain (northern Japan) using groundwater-heat transport model and GIS.

2. STUDY AREA

Tsugaru Plain is situated in the western part of Aomori Prefecture in Japan (Fig. 1) with an area of about 647 square km. This lowland is mainly formed by alluvial deposits carried by Iwaki River and its tributaries. It faces the Sea of Japan to the west and surrounded by Tsugaru Mountain range in the north and east, Iwaki Mountain in the west, and Shirakami Mountain range in the south. Surrounding highlands consist of diluvium deposits, while quaternary volcanic products are distributed over base of Iwaki Mountain. Quaternary deposits mainly consist of fine sand, silt, gravel and intercalated clay layers which form the main aquifers of the plain.

3. REGIONAL SCALE ANALYSIS MODEL

For the assessment of potentiality of GCHP system, groundwater flow system as well as distribution of subsurface temperature must be comprehended in detail. For that purpose, a regional scale 3D analysis model (Fig. 2) was developed using finite element software FEFLOW (Diersch, 2005). Model boundary was defined along dividing ridges surrounding the plain. At north-west, the boundary was set along the southern bank of Lake Jusan. Horizontal dimensions of the model were 64km and 78km in east-west and north-south directions respectively. In the model, layers 1 to 4 belonged to Quaternary System. Layers 5 to 7 belonged to Neogene and layers 8 to 12 belonged to Paleogene, both of which correspond to Tertiary System. Thickness of these layers varied significantly at different locations. Thickness of the Quaternary System ranged from 0.4m to 1351.3m, that of Neogene varied from 0.3m to 1482.3m and that of Paleogene ranged from 1013.3m to 2881.4m. Basal elevations of geological layers were referred from Koshigai et al. (2011).

With this geological model, saturated steady state simulation of groundwater flow and heat transport was conducted. Regarding boundary conditions of groundwater flow system, top of the model was fixed by water table, while model

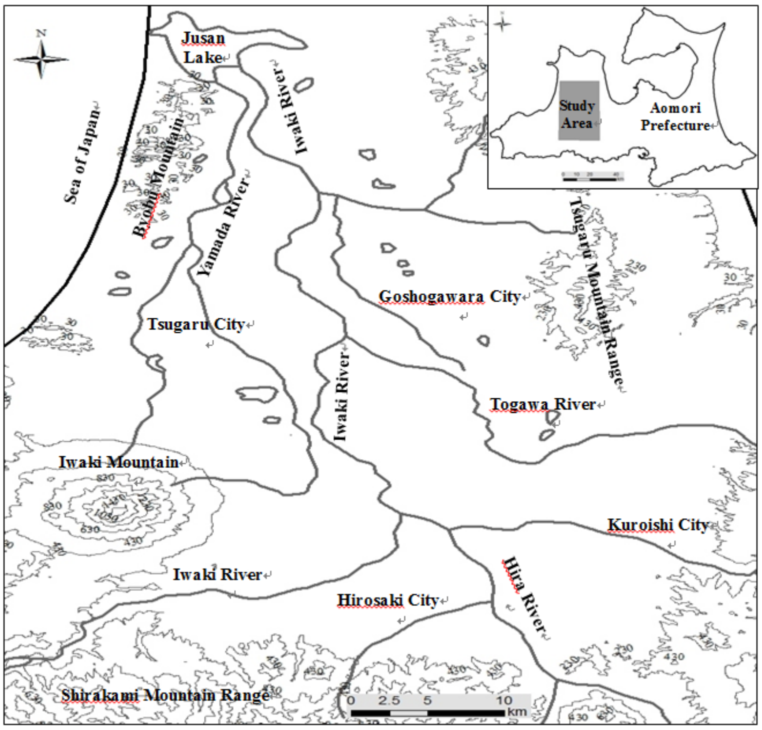


Fig.1 Location of Tsugaru Plain

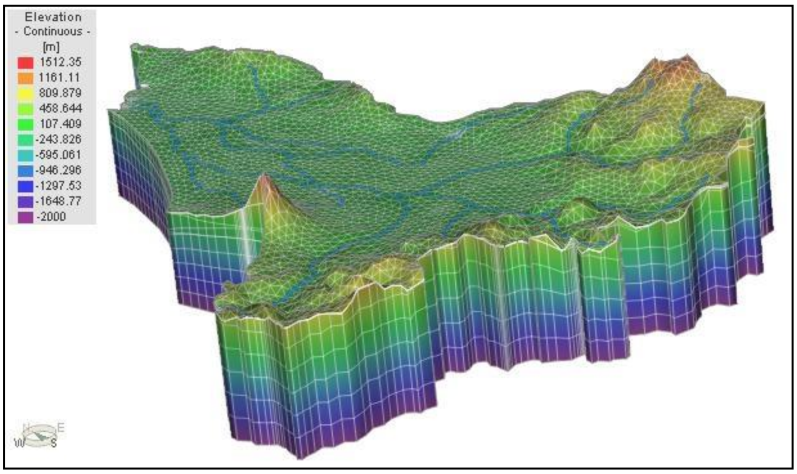


Fig. 2 Regional scale analysis model of Tsugaru Plain

bottom was treated as impermeable boundary and lateral sides were set as no flow boundaries. For boundary conditions of heat transfer, top and bottom of the model were fixed by time constant temperature boundaries, and lateral sides were set as adiabatic allowing heat transfer by groundwater convection only. Temperature distribution at model top was estimated on the basis of annual average temperature at Goshogawara City of 10.5^{o}C and assuming a decrement rate in ambient temperature with elevation of 0.7^{o}C/100m. Temperature distribution at bottom was estimated based on the surface temperature distribution, using a geothermal gradient of 3^{o}C/100m referred from Geological Survey of Japan (2004).

Model parameters adopted for geological layers are shown in Table 1. Hydraulic and thermal conductivities of geological layers were determined by trial and error method based on the comparison of simulation results with the data of past studies and actual field condition. Porosity and heat capacity were referred from Japan Society of Thermophysical Properties (1990) on the basis of types of geological layers.

In absence of measured hydraulic heads of observation wells, computed results of groundwater flow system were indirectly verified by comparing them with results of past studies and literature values. At Hirosaki City located in the southern part of the plain, calculated hydraulic head was in the range of 30m. The hydraulic head presented by Sakai

(1960) in that city was also around 30 m. Similarly, at Kuroishi Shogyo high school of Kuroishi City located in the south eastern part of the plain, calculated hydraulic head was 47.1m. Hydraulic head measured by Machida and Yasukawa (2008) at the same high school was 47m, very close to the calculated value. Depth of water table from the ground surface was found to be shallow in most of the areas of the plain. Machida and Yasukawa (2008) and Aomori Prefecture (2011) also showed similar results, implying the sustainable operation of GCHP system in terms of groundwater availability and saturation of geological layers.

Table 1 Model Parameters

	Quaternary System (1-4 Layers)	Tertiary System	
		Neogene (5-7 Layers)	Paleogene (8-12 Layers)
Hydraulic Conductivity (m/s)	5×10^{-5}	3.4×10^{-6}	2.4×10^{-7}
Porosity (-)	0.4	0.1	0.1
Heat Capacity (J/m^3K)	4.9×10^6	4.9×10^6	4.9×10^6
Thermal Conductivity (W/mK)	1.2	1.5	1.5

Natural water bodies such as springs, lakes and ponds are generally formed by the up flowing groundwater. Simulation results were further validated by inspecting the path of simulated flow at natural water bodies, confirming if groundwater was flowing in upward direction. At Tomita Spring located in Hirosaki City, groundwater was found to be flowing in upward direction (Fig. 3). Likewise, up flow was also found at other natural lakes and ponds. It can be said that calculated results of groundwater flow were consistent with the natural condition and data of past studies.

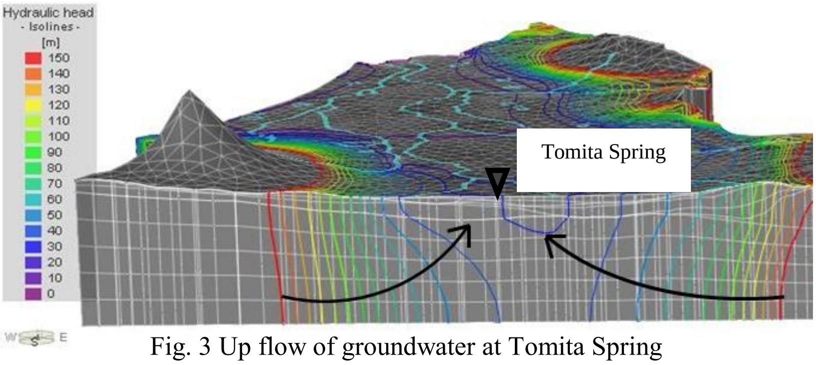


Fig. 3 Up flow of groundwater at Tomita Spring

Regarding the computed results of subsurface temperature distribution, they could not be verified with measured vertical temperature profiles because observation wells were lacking. Hence, the results were compared with the observed temperature data of hot springs located in the plain (Fig. 4), which were referred from Geological Survey of Japan, 2002.

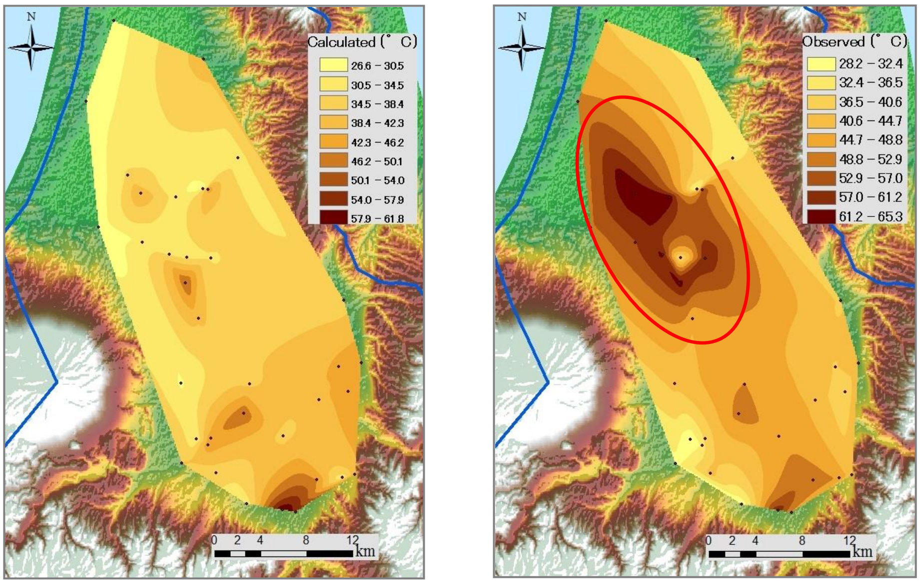


Fig. 4a Calculated data

Fig. 4b Observed data
(Geological Survey of Japan, 2002)

Fig. 4 Comparison of calculated subsurface temperature with observed data of hot springs

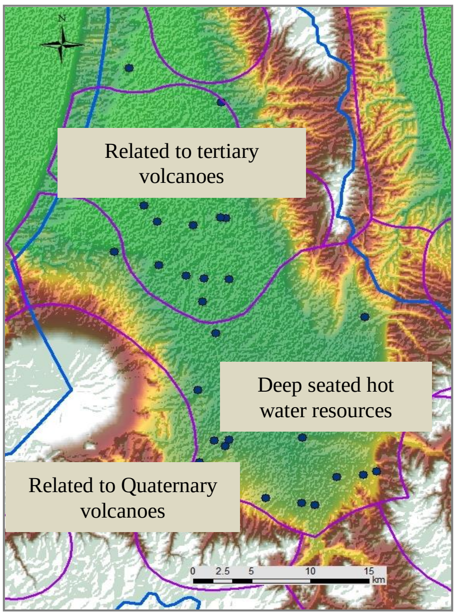


Fig. 5 Classification of geothermal resources (Geological Survey of Japan, 2002)

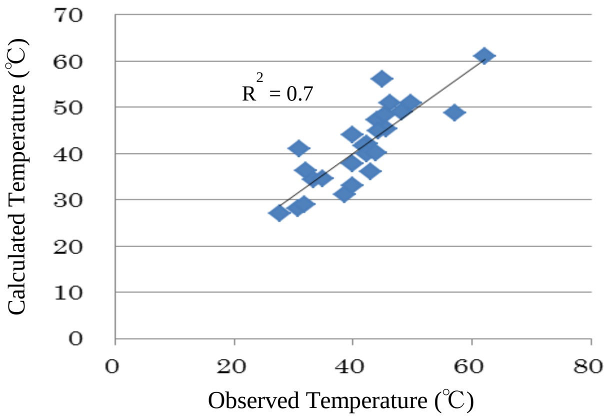


Fig. 6 Comparison of calculated and observed temperature of hot springs located at upstream region classified as deep seated hot water resources

Calculated temperature data corresponding to the locations of hot springs were extracted from the results of analysis model and compared with the observed data. Observed temperature data were found higher at the downstream region around Goshogawara City (area marked with red line in Fig. 4b). In order to find out the reason for this higher observed temperature, data of geothermal resources were referred from Geological Survey of Japan (2002). From data related to geothermal resources (Fig. 5), the area with higher temperature was found to be classified as the resource area related to tertiary volcanoes or old magma. In our analysis model, data related to volcano was not incorporated and this could be the reason that calculated temperature at downstream area was lower. However, at upstream area regarded as deep seated hot water resources, calculated temperature was almost similar to the observed data (Fig. 6).

4. DEVELOPMENT OF POTENTIAL MAPS FOR GCHP SYSTEM

Groundwater flow system and geological condition strongly affects heat exchange rate of ground heat exchanger. Hence, potential maps should be prepared on the basis of local hydrogeological and thermal information that can contribute to the subsequent reduction of installation cost and maximization of heat exchange rate. For this purpose, thematic maps of groundwater velocity, subsurface temperature, water table depth and sand-gravel ratio in geological strata were prepared using GIS (Fig. 7) based on the results of analysis model. Groundwater velocity, subsurface temperature and sand-gravel ratio were taken as average value up to 50m below surface.

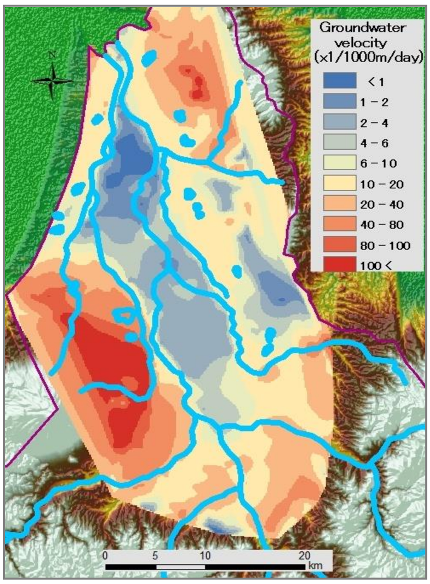


Fig. 7a Groundwater velocity

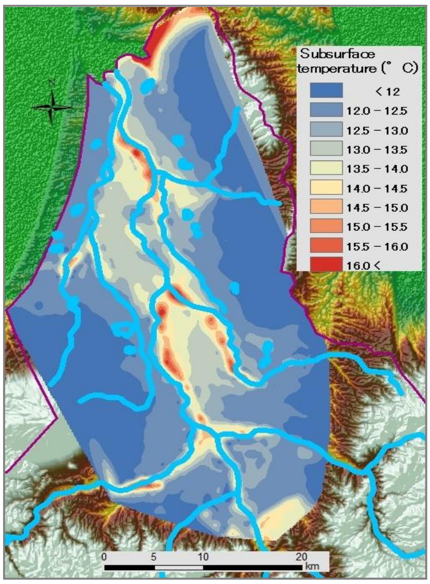


Fig. 7b Subsurface temperature

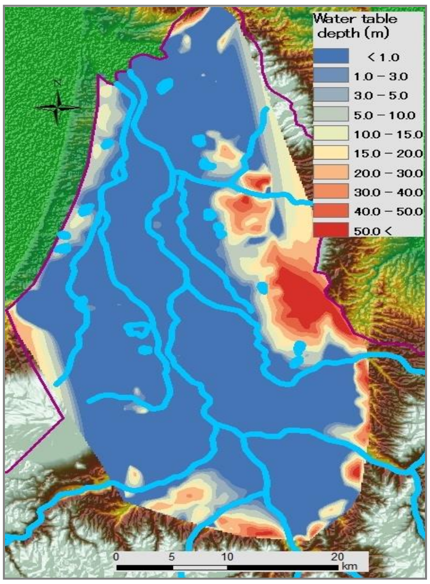


Fig. 7c Water table depth

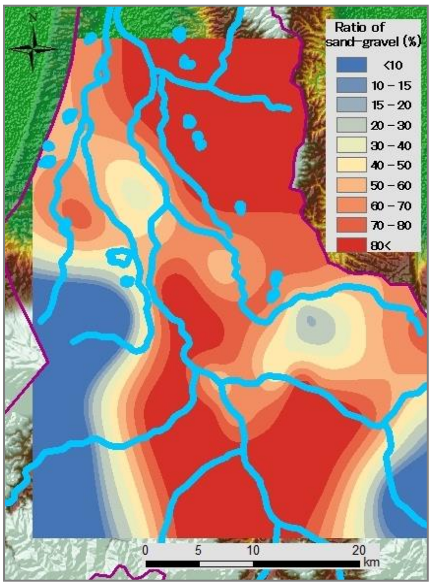
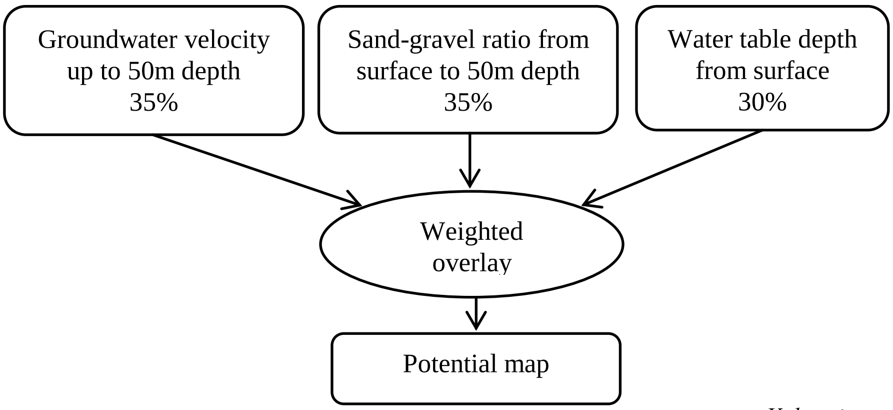


Fig. 7d Sand-gravel ratio

Fig. 7 Thematic maps in GIS

Table 2 Reclassification of thematic maps

Groundwater velocity Index class (x 10^{-3}m/day)	Sand-gravel ratio Index class (%)	Water table depth from surface Index class (m)	Subsurface temperature Index class (˚ C)	Grade
< 1	<10	50 <	< 12	1
1 - 2	10 - 15	40 - 50	12 - 12.5	2
2 - 4	15 - 20	30 - 40	12.5 - 13	3
4 - 6	20 - 30	20 - 30	13 - 13.5	4
6 - 10	30 - 40	15 - 20	13.5 - 14	5
10 - 20	40 - 50	10 - 15	14 - 14.5	6
20 - 40	50 - 60	5 - 10	14.5 - 15	7
40 - 80	60 - 70	3 - 5	15 - 15.5	8
80 - 100	70 - 80	1 - 3	15.5 - 16	9
100 <	80 <	< 1	16 <	10



Values in percentage = Weightage

Fig. 8 Overlay model for air conditioning

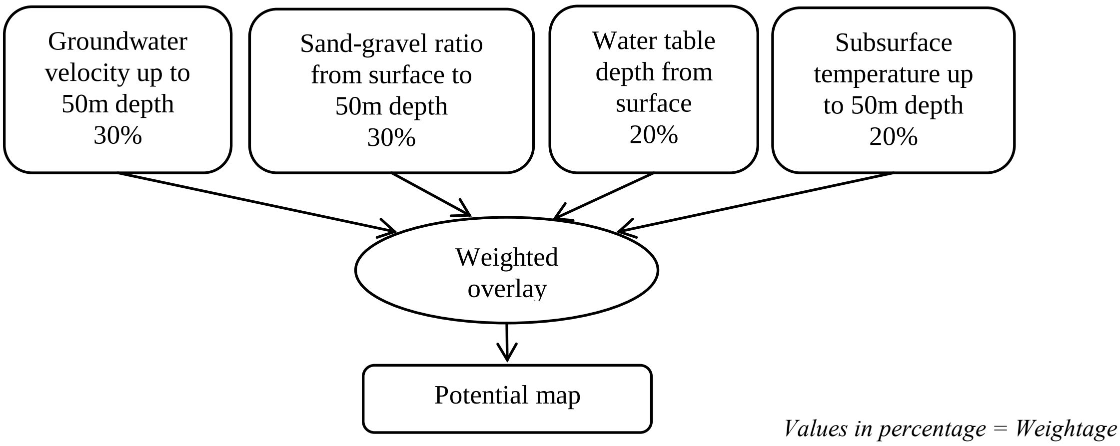
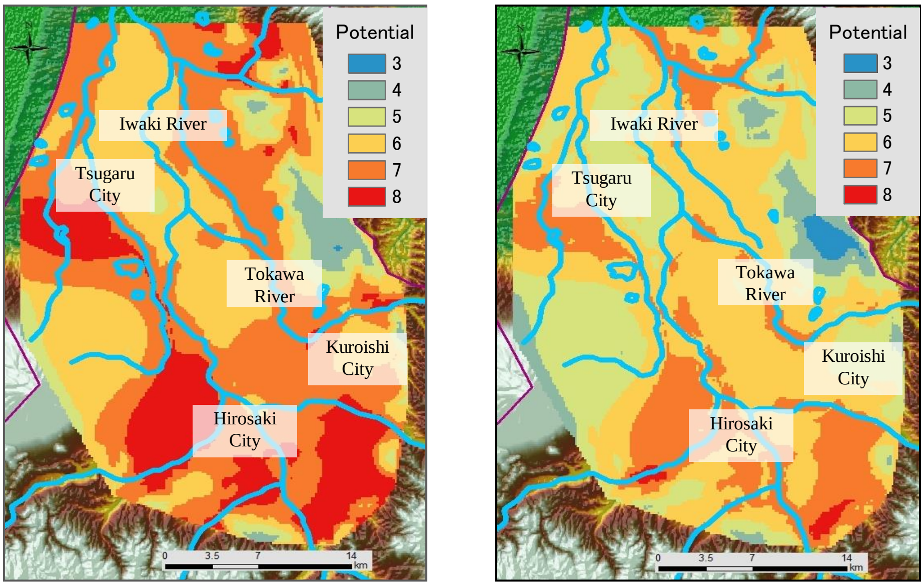


Fig. 9 Overlay model for snow melting

In this study, potential maps for air conditioning (space heating and cooling) and snow melting were prepared by overlaying the prepared four thematic maps in GIS using overlay model (Fig. 8 and Fig. 9). Parameter of each map was reclassified into index classes and each index class was assigned a grade ranging from minimum 1 to maximum 10 (Table 2). Higher the grade, higher is the potential for GCHP system installation. Values in percentage in figures 8 and 9 represent weightage of each thematic map used for overlaying in GIS.

In air conditioning case, subsurface temperature was not considered in the overlay model. The reason is higher and lower subsurface temperatures both are equally important for space heating and space cooling respectively. However, in snow melting case, higher subsurface temperature is more effective and advantageous. Hence, subsurface temperature was considered in snow melting case. Weightage set for the air conditioning case were 35% for groundwater velocity, 35% for sand-gravel ratio and 30% for water table depth. Regarding the snow melting case, weightage used were 30% for groundwater velocity, 30% for sand-gravel ratio, 20 % for water table depth and 20% for subsurface temperature. Weightage was set based on the classification of parameter (Table 2) of each thematic map. Maps were overlaid based on grades applied to each cell and weightage assigned to each maps, resulting potential maps (Fig. 10)



Air Conditioning Snow Melting

Fig. 10 Potential Maps

In the legend of potential maps, higher the number higher is the potential for the installation GCHP system. Lower potential does not mean that GCHP system cannot be installed. It can be installed but longer length of ground heat exchanger is required and hence the higher cost. Major cities of Tsugaru Plain such as Tsugaru City, Hirosaki City etc. showed higher potential with favorable geological and hydrological condition. In eastern part of the plain particularly at the east of Tokawa River, potential is lower as this area is characterized by lower groundwater velocity, deep water table and lower subsurface temperature. Distribution of higher potential area is at large in air conditioning case, however, snow melting is also suitable in these areas. This kind of potential maps that illustrate the variation of potentiality is essential to adopt suitable location for the optimum design of GCHP system.

5. CONCLUSION

Groundwater flow system and subsurface temperature distribution of Tsugaru Plain was comprehended by developing a regional scale numerical model. Thematic maps of groundwater velocity, subsurface temperature, water table and sand-gravel ratio showing the variation of their respective parameters can be regarded significant for the proper siting of GCHP system. Potential maps developed on the basis of these thematic maps can be effectively utilized to determine suitable location for air conditioning and snow melting purposes using GCHP system. The maps can further assist for appropriate design and economic feasibility of the system.

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