Int. J. of GEOMATE, Sept., 2013, Vol. 5, No. 1 (Sl. No. 9), pp. 666-671
Geotec., Const. Mat. & Env., ISSN:2186-2982(P), 2186-2990(O), Japan

SPATIAL DISTRIBUTION CHARACTERISTICS OF SUBTERRANEAN HOT WATER EVALUATED USING WATER QUALITY CONCENTRATION DATA

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ABSTRACT: Spatial distribution characteristics of subterranean hot water were indexed using correlation coefficient's (*R*) *p*-values for hot spring water quality indicators. For example, in a case where the *p*-value of *R* was smaller than 5%, the correlations of a set of water qualities for two hot springs were significant. In this study, in a dense hot spring area, the minimum distance with a *p*-value greater than *Pc* (critical *p*-value) was proposed as a stochastic and critical distance (*Xc*) for both new and existing hot spring owners. By using data from 10 hot springs in each area, 45 sets of distances and *p*-values were examined. Of the five areas examined, three and four *Xc*s more than 1,000m were found for *Pc* 1% and *Pc* 5%, respectively. The experimental relation between the given *Xc* and the hot spring depth could not be confirmed. Results indicate that the influence of water quality from new hot springs located outside of the *Xc* range is not always insignificant, even though the water quality of the new hot springs should primarily influence existing springs located within the *Xc* range.

Keywords: hot spring, subterranean hot water, hot springs law, correlation coefficient, p-value

1. INTRODUCTION

In Japan, in areas where wells for hot spring spas are numerous, decaying water quality has been observed. To combat this problem, the “Guideline for the protection of hot spring resources” was developed under the Hot Springs Law by the Japanese Ministry of the Environment [1].

A water source is determined to be a hot spring by the “Hot Spring Law” (Onsen-ho), if the hot water discharged from underground is equal to or above 25°C. When it is below 25°C, it must satisfy at least one of the 19 elements listed in Table 1.

According to the guidelines [1], the limiting distance for new wells, *Xg*, is 300–500m, as set forth by the questionnaires administered in 23 prefectures. *Xg* being the critical limiting distance proposed in practice for public judgment (m). Some *Xg*s were given numerically by questionnaires, water balance and heat balance. From the viewpoint of water balance, *Xg* is 406 m. For deep hot springs, *Xg*s are 1,000–2,000 m. By calculating heat balance, *Xg*s are 1,030–1,780 m. On account of numerous hypotheses applied, the logic of employing these distances is not particularly strong. Hence, using critical limiting distance, Xg, is very simple.

The depth of hot spring wells can substantially differ. Wells with depths of more than 1,000 m are called deep hot springs, whereas those with depths lower than 1,000 m are called shallow hot springs. In order to receive authorization for a hot spring, it is necessary to obtain water quality data. Therefore, much hot water quality data is available. In this study, we focused on five areas with available hot spring water quality data. Ten hot water springs were used for each area, totaling to 50 hot springs. Particular types of water qualities were selected to determine correlations among the hot springs.

Hot springs with similar water quality may have the same source. Digging a new hot spring with a similar water quality is a potential water resource hazard for the existing hot spring owner. If the water quality difference of two hot springs can be estimated by the distance between them, a parameter that is easily determined, this could help in avoiding such hazards. Therefore, the water quality differences between two hot springs were discussed relative to the distance between the hot springs. For analysis, the following three hypotheses were made.

1) Steady state hypothesis is used. The correlation coefficient (*R*) of water quality between two hot springs can be numerically given as a constant number by a stochastic method.
2) In cases where the correlation is significant, as the *p*-value of *R* is smaller than the critical value *Pc*, the water source or root of the flow is expected to be near.
3) In cases where the water source or root of the flow is near, digging a new hot spring may affect the

existing hot spring.

Estimation of the critical distance *Xc* would assist both a new owner digging a new hot spring and the existing hot spring spa owner. In this study, *Xc* is the critical distance determined by using stochastic method, which is numerically given by evaluating the similarity of certain chemical data measured in each of the hot springs.

2. OBJECTIVES

Under all three hypotheses given in the Introduction, three objectives were created, which are mentioned as follows:

1) Confirm how the combination samples of *X* and *p*-value will be classified by *Xc* and *Pc*.

X being the distance between the new and existing hot spring (m).

2) Determine whether *Xc* varies with hot spring depth.

3) Clarify the essential meaning of *Xg*s and *Xc*s by discussing the difference between them.

These three objectives were examined by collecting and analyzing water quality data of existing hot springs.

3. CALCULATIONS

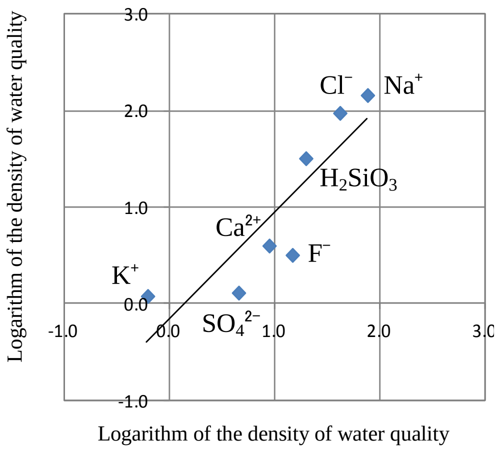
The mutual relations among the logarithm values for seven types of water quality indicators (ppm) are illustrated in Fig. 1. A logarithmic function was used because of the varying order of magnitude for water quality parameters.

The correlation value for both hot springs can be obtained using a stochastic method. Seven types of water quality indicators, shown in Table 2, were selected on the basis of the following three points: (1) The hot spring water qualities as defined by the ministry in the hot-spring standard (Table 1). (2) The water qualities derived from previous hot springs, shown in [2][3]. (3) The geology-based water qualities shown in Piper's trilinear diagram. In this study, we selected Na, K, Ca, F, Cl, SO_4, and H_2SiO_3. Because these seven water quality indicators were used, the data number *n* for determining *R* is seven.

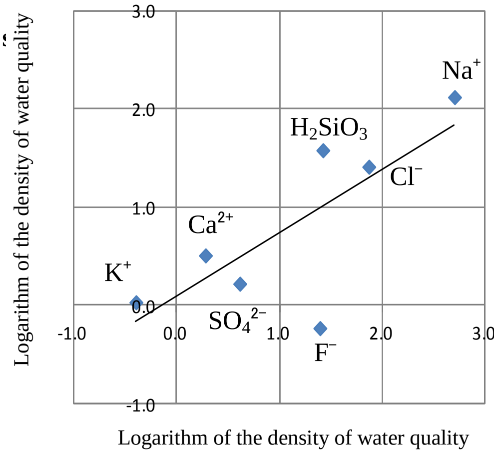
The *p*-value was used as the index that demonstrates the significance of the correlation *R*. Although the procedure for calculating *p*-value using

Table 1 Standard of hot spring spa

temperature	≥25°C
total soluble component	≥1,000 mg/kg
CO_2	≥250 mg/kg
Li^+	≥1 mg/kg
Si^{2+}	≥10 mg/kg
Ba^{2+}	≥5 mg/kg
Fe^{2+},Fe^{3+}	≥10 mg/kg
Mn^{2+}	≥10 mg/kg
H^+	≥1 mg/kg
Br^-	≥5 mg/kg
I^-	≥1 mg/kg
F^-	≥2 mg/kg
$HAsO_4^{2-}$	≥1.3 mg/kg
$HAsO_2$	≥1 mg/kg
S	≥1 mg/kg
HBO_2	≥5 mg/kg
H_2SiO_3	≥50 mg/kg
$NaHCO_3$	≥340 mg/kg
Rn	≥2 × 10^{-9} Ci/kg
Ra	≥1 × 10^{-8} mg/kg



(a) A case where *p*-value is 1%



(b) Case where *p*-value is 5%

Fig. 1 Examples of a set of data

R and *n* is essential, it is widely explained in other books and hence not elaborated in this study.

When the *p*-value of *R* is larger than *Pc*, the correlation is not significant. From the second hypothesis given in the Introduction, a high *p*-value suggests that digging a new hot spring will not affect the water of the existing hot spring.

In sections I and II of Fig. 2, where the *p*-value is more than the threshold value *Pc*, the correlation is not significant. In section I, there is no theoretical plot. Therefore, in this study, *Xc* is defined as the minimum distance *X* of the plots in section II. The possibility that the new hot springs affect the existing ones is presumed small for this section.

On the other hand, in sections III and IV, the correlation is significant. For the range IV plot group, even if the distance is longer than *Xc*, the correlation of water quality may be significant. Therefore, the new hot spring may affect the existing spring.

4. HOT SPRINGS USED FOR ANALYSIS

In this study, the prefecture shown in Fig. 3 was used. Ten spa facilities for each of the five areas were selected; that is, the water quality of 50 hot springs was used. By combining all hot springs in each area, a total of 45 sets of two hot spring combinations were possible (i.e., 45 distances *X* and *R* coefficients for each area).

As shown in Table 3, in area 1, most hot springs were deep. On the other hand, in area 5, which was well known for its hot springs, most hot springs were shallow. In areas 2, 3, and 4, deep hot springs were more in number than shallow hot springs.

5. RESULTS

As some of the water qualities are numerically zero, the logarithm of all data points could not be calculated. As the data number (***n***) was expected to be constant, the *R* values for such cases were not used in this study. Therefore, the given numbers of *R* were not always 45, as shown in Table 4. For areas 1–5, the numbers of plots were 36, 45, 45, 36, and 45, respectively.

Table 2 Dataset used for analysis

water quality	chemical symbols
Sodium ion [2, 3]	Na^+
Potassium ion [2, 3]	K^+
Calcium ion [2, 3]	Ca^{2+}
Fluoride ion [1, 2]	F^-
Chloride ion [2, 3]	Cl^-
Sulfuric acid ion [2, 3]	SO_4^{2-}
Metasilicic acid [1, 2]	H_2SiO_3

1: water quality shown in the hot-spring standard
2: water quality shown in [2] and [3]
3: water quality used in the trilinear diagram

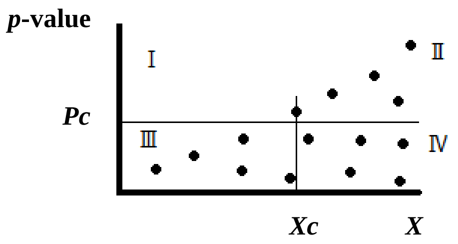


Fig. 2 The condition *Pc* and selected *Xc* on *X*-(*p*-value) plane, where each point indicates the result for the hot-spring combinations

Table 3 Major depth types for each area

area	deeper than 1,000 m	shallower than 1,000 m	the major type
1	9	1	deep
2	6	4	deep
3	7	3	deep
4	6	4	deep
5	1	9	shallow

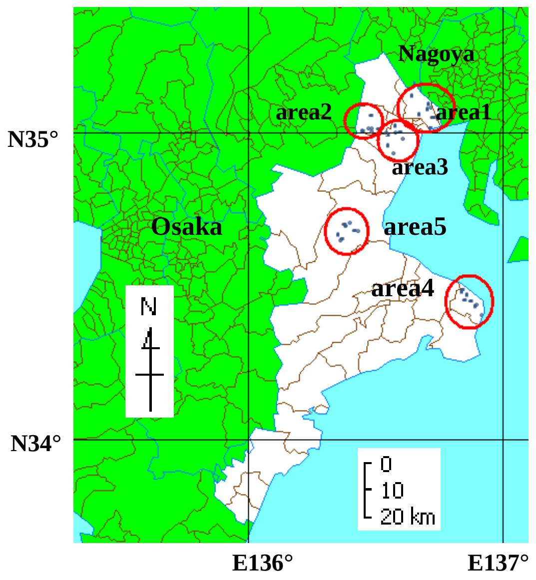


Fig. 3 Map of hot spring locations in each area

By using the concept of *Xc* and *Pc* as shown in Fig. 2, the combinations of the *X*s and *p*-values were separated by *Pc* 5% as shown in Figs. 4 (1)–5). There is no theoretical plot in section I because the vertical line is drawn for making such a situation. Alternatively, there was no area without plots in the section IV. This result was the similar for the combination of *X*s and *p*-values separated by *Pc* 1%.

6. DISCUSSION

*Xc*s can also be explained using Figs. 5 (1)–(5), where each hot spring is shown as a plot. The five figures in the left-hand column represent the raw data.

The middle five figures present the distances whose *p*-values are less than 5%. The right-hand-side figures show the distances whose *p*-values are less than 1%.

In Figs. 5 (1)–(5), if the group of solid lines show almost the same direction in one area, and yet if such a group is not shown in the figures on the left, it suggests that underground the water is flowing in the same ground layer. However, this type of grouping of solid lines was difficult to see.

1) The samples classified by *Xc* and *Pc*

As the combination samples of *X*s and *p*-values were classified as shown in Figs. 4 (1)–(4), each could be counted without the samples having water quality that is numerically zero (Table 4).

The four samples having the smallest distance had *p*-values of 0.00001, 0.00040, 0.00202, and 0.00000 for distances of 0, 187, 331, and 392 m, respectively. The order of these numbers means that the *p*-value becomes very small as distance *X* becomes very small. Because such a small *X* is rare, it was lucky for us that the *p*-value could be obtained.

For large distance *X*, the numbers of the samples for which there was a combination of *X* and *p*-value were not small, as shown in the section IV in Table 4. Therefore, digging a new hot spring in such cases may affect the existing hot spring located at a large distance.

2) Order of *Xc* along the depth

In Table 5, for the four deep hot spring areas (areas 1–4), *Xc*s are distributed between 659 and 6641 m. For the shallow hot spring area (area 5), *Xc*s are distributed to 1512 m. Therefore, the relationship between depth and *Xc*s was not a simple one.

3) Difference of the meaning about *Xg* and *Xc*

Prior to the analysis, the given *Xc*s were numerically nearer to *Xg*s more than what was

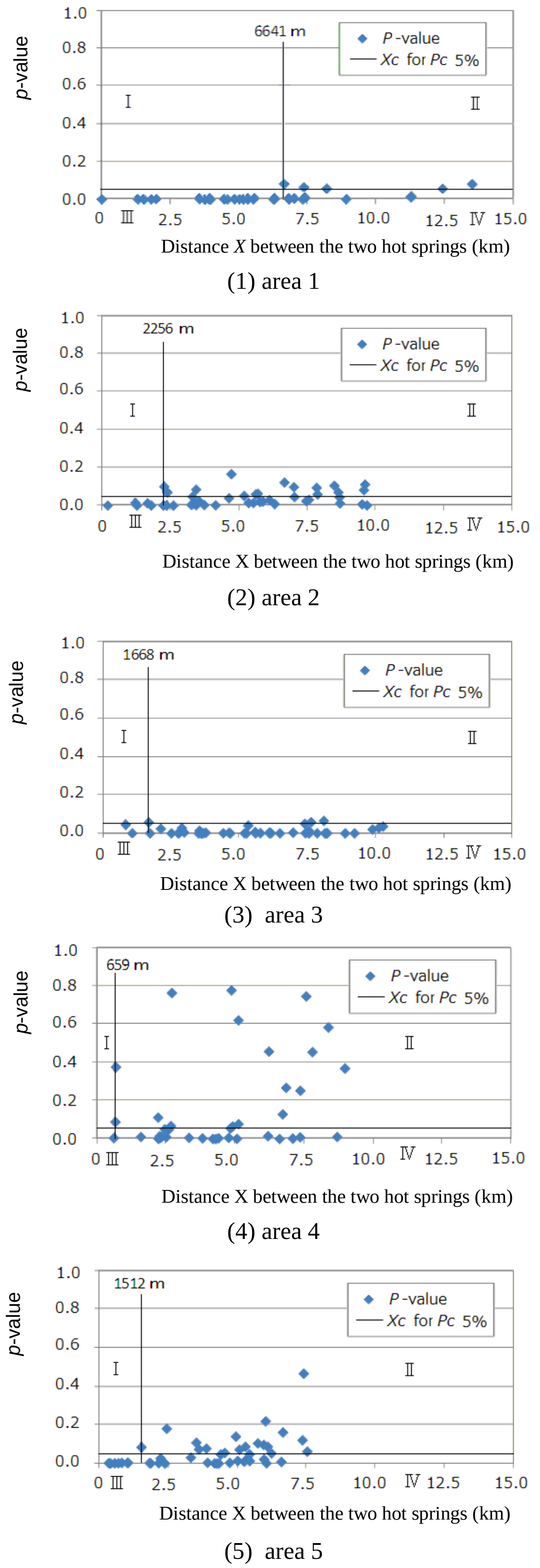


Fig. 4 Given *p*-values versus distance between two hot springs, in which *Pc* 5% is applied

expected, as depicted in the second row of Table 6. As shown in Table 4, although section I is empty, there are many plots in section IV. This indicates that the *p*-value which is larger than *Pc* cannot be distinguished by distance *X* alone. Thus, correlation of the new hot spring's water quality with an existing spring located outside of the *Xc* range is not always insignificant as shown in column (4) of Table 6. This is despite the fact that correlation of the new hot spring's water quality with an existing spring located within the *Xc* range should always be significant, as shown in column (2) of Table 6.

7. CONCLUSIONS

With regard to the unclear phenomena occurring very deep in the ground layer, the simple stochastic view was applied because we were expecting some simple rules. Most of the results seem to give some power to existing hot spring owners. The results, however, were not good for new hot spring owners as the critical limiting distance was confirmed to be insufficient for explaining the sustainable digging of hot spring.

Table 4 Number of the samples of the set of *X* and *p*-value

Area	***Pc* 5%**					***Pc* 1%**				
	I	II	III	IV	total	I	II	III	IV	total
1	0	5	24	7	36	0	7	24	5	36
2	0	15	6	24	45	0	31	1	13	45
3	0	3	2	40	45	0	13	0	32	45
4	0	19	1	16	36	0	25	1	10	36
5	0	12	7	26	45	0	26	7	12	45

Table 5 Given critical distance, where *Pc* indicates critical *p*-value

Area	Major type of depth	*Xc*	
		Pc 5%	***Pc*** 1%
1	deep	6641	6641
2	deep	2256	1200
3	deep	1668	824
4	deep	659	659
5	shallow	1512	1512

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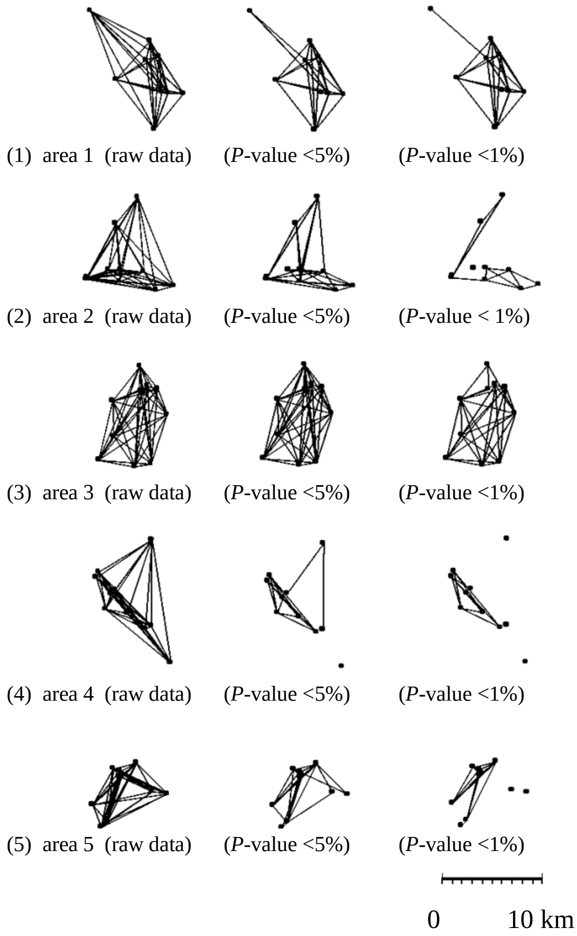

Fig. 5 Distances given for *Pc* 5% or *Pc* 1%

Table 6 Difference between *Xg* and *Xc*

Critical distance	***Xg*** shown in [1]	***Xc***
Reason of the distance	Questionnaires, water balance, and heat balance.	Stochastic approach
Order of the distance	300–500m or 1,000–2,000m as explained in Introduction	659–6,641m from Table 5
Hot springs at a distance smaller than the critical distance	(1) mutually influenced.	(2) influenced in the section III
Hot springs at a distance larger than the critical distance	(3) not influenced.	(4) not influenced in the section II

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Int. J. of GEOMATE, Sept., 2013, Vol. 5, No. 1 (Sl. No. 9), pp. 666-671.
MS No. 3257 received on May 9, 2013 and reviewed under GEOMATE publication policies.

Pertinent discussion including authors' closure, if any, will be published in the Sept. 2014 if the discussion is received by March, 2014.
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