Characterizing Geothermal Surface Manifestation Based on Multivariate Geostatistics of Ground Measurements Data

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Abstract. Mt. Wayang Windu is one of geothermal field located in West Java, Indonesia. The characterization of steam spots at surface manifestation zones based on the soil physical measurements of the area is presented in this study. The multivariate geostatistical methods incorporating the soil physical parameter data were used to characterize the zonation of geothermal surface manifestations. The purpose of this study is to evaluate the performance of spatial estimation method of multivariate geostatistics using Ordinary Cokriging (COK) to characterize the physical properties of geothermal surface manifestations at Mt. Wayang Windu. The COK method was selected because this method is favorable when the secondary variables has more number than the primary variables. There are four soil physical parameters used as the basis of COK method, i.e. Electrical Conductivity, Susceptibility, pH, and Temperature. The parameters were measured directly at and around geothermal surface manifestations including hot springs, fumaroles, and craters. Each location of surface manifestations was measured about 30 points with 30 x 30 m grids. The measurement results were analyzed by descriptive statistics to identify at the nature of data. The correlation among variables was analyzed using linear regression. When the correlation coefficient among variables is higher, the estimation results is expected to have better Linear Coregionalization Model (LCM). LCM was used to analyze the spatial correlation of each variable based on their variogram and cross-variogram model. In oder to evaluate the performance of multivariate geostatistical using COK method, a Root Mean Square Error (RMSE) was performed. Estimation result using COK method is well applicable for characterizing the surface physics parameters of radar images data.

Keywords: surface manifestations, Linear Model Coregionalization, multivariate geostatistics, cokriging, Root Mean Square Error

1. Introduction

Mt. Wayang Windu Geothermal Field (WWGF) is an area that has geothermal activity and now in production. The surface manifestation zones at WWGF can be characterized based on the soil physical parameters. The multivariate geostatistical methods incorporating the soil physical parameter as primary data with remote sensing images as secondary data were used to characterize the zoning manifestations. Ordinary Cokriging (COK) method has advantage to provide more accurate estimation and knowable relationships of spatial correlation among variables.
The use of remote sensing images data as secondary variable has its own advantages as it can cover a wide area, so the number of secondary data is much more than primary one. When the secondary variables are much more than the primary ones, COK method generally produces more advantages [1].

The purpose of this study is to determine the nature characteristics of physical parameters i.e. electric conductivity, susceptibility, temperature, and pH of surface manifestation around WWGF using roughness data of the radar images as secondary data.

2. Study Area

WWGF took the name after Mt. Wayang and Mt. Windu, the two small lava domes without eruption history [2]. The field is located at Pangalengan town, approximately 40 km to the south of Bandung city, the capital of West Java Province, Indonesia (see Figure 1). The elevation of Wayang Windu is between 1500 – 2100 m above sea level [3].

Wayang Windu study area includes the Wayang Windu geothermal systems associated with the dominant steam fluid caps. WWGF associated with Mt. Malabar, large volcano-type stratovolcano composed of lava, breccia, lava and dacitic tuffs, and andesite.

Several thermal manifestations including fumaroles, hot springs, mud pools and altered soil are located along the slopes of the mountain range. Fumaroles which are located between Mt. Wayang and Mt. Windu show temperatures between 93°C to 96°C, and slightly superheated if we compared to the normal water boiling point at altitudes of 2000 m. Hot springs which are located at altitudes between 1495 m and 1985 m reach temperatures from 41°C to 88°C. The water discharge of hot springs is bicarbonate type, except for the hot springs located near fumaroles discharged acid sulphate water.

The lithology at WWGF consists of four main units, which were subdivided by Alzwar et al [4] into: the older Malabar-Bedil andesite unit, the Kancana lavas unit, the Malabar-Tilu volcanic unit, and the younger Wayang volcanic unit. According to Bogie et al, the geothermal system at Wayang Windu is classified as transitional between vapour and liquid dominated systems [5].

![Figure 1](image)

Figure 1. The location of study area at WWGF in West Java, Indonesia shows the lane of geothermal prospecting in gray arc segments [2]. The inset showing local of study area presented by surface roughness model using HV and VH polarized mode.
3. Material and Method

Ordinary Cokriging (COK) is an estimation technique that ensures the value of variable estimated in a point in space, on the basis of neighbouring values of one or several other variables. The COK estimate is a linear combination of both primary and secondary data values [6].

COK therefore is applicable specifically for different but correlated variables, non-collocated variables of different quality that are sampled at different density across a domain. The variogram and cross-variogram can be used in COK system only provided that the requisite constraints on COK weights are met. The cross-variogram can be transformed into a corresponding cross-covariance. The cross-covariance can be modelled using linear coregionalization model to be used in COK system. Since a single secondary variable ($Y$) is considered, the COK estimator of primary variable is:

$$Z_{COK}(u) = \sum_{\alpha=1}^{n} \lambda_{\alpha}(u) Z(u_{\alpha}) + \sum_{\beta=1}^{r} \lambda_{\beta}(u) Y(u_{\beta})$$

where $\lambda_{\alpha}$ represents the weights applied to $n$ primary data ($Z$), $\lambda_{\beta}$ represents the weights applied to $r$ secondary data ($Y$), and the bold $u$ identifies a vector [7].

The model of spatial structure is represented by semi-variogram, $\gamma(h)$. It represents the average variance between observations data separated by distance $h$, calculated by:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{n} (Z(x_{i}) - Z(x_{i} + h))^2$$

with $Z(x_{i})$ is the measurement at location $x_{i}$, $Z(x_{i} + h)$ is the measurement at location $x_{i} + h$ , $\gamma(h)$ is the variogram for distance vector (=lag) $h$ between measurements $Z(x_{i})$ and $Z(x_{i} + h)$, $N(h)$ is the number of couples measurements separated by distance $h$.

Cross-variogram is used to obtain the covariance between two variables, i.e. ground truth and roughness data. Cross-variogram values are calculated directly from the samples data (co-variable) using the formula:

$$\hat{\gamma}_{AB}(h) = \frac{1}{2N(h)} \sum_{i} \sum_{j} \{Z_{A}(x_{i}) - Z_{A}(x_{j})\} \{Z_{B}(x_{i}) - Z_{B}(x_{j})\}$$

where $\hat{\gamma}_{AB}(h)$ is the cross-variogram value at distance $h$ [8].

The primary data is derived from field data (ground truth) around the location of geothermal manifestations such as craters and hot springs. Variables of field data are Electric Conductivity, Susceptibility, pH, and Temperature. The fourth parameter is used as reference to extrapolate the whole study area.

Secondary data is derived from the scene backscattering intensity data of the phased array type L-band Synthetic Aperture Radar (PALSAR) on board the Advanced Land Observing Satellite (ALOS), consists of four polarization types known as: HH, HV, VH, VV. ALOS PALSAR is an active microwave sensor using wavelength of 23.6 cm, thus the sensor is not affected by the presence of clouds, and observations is time independent. The backscattering signal $\sigma^0$ is function of roughness materials at surface $h_{o}$, incident angle $\theta_{i}$, and scattering matrix element $\alpha$ can be calculated as follows:

$$\sigma^0 = (4k^4h_{o}^2\cos^4\theta_{i})|\alpha|^2\omega$$

where $\omega$ is a spectrum density of surface topography [9].

The initial surface roughness model was used as basis sensitivity identification to the surface roughness at the field. The model could be calculated for each polarization type using the following equation [10]:

$$Z_{COK}(u) = \sum_{\alpha=1}^{n} \lambda_{\alpha}(u) Z(u_{\alpha}) + \sum_{\beta=1}^{r} \lambda_{\beta}(u) Y(u_{\beta})$$
\[ h_0(\eta \xi) = \lambda \sqrt{\frac{1}{60} \ln \left( 1 - 10^{0.1 \sigma_{\eta \xi}^0 \cos \theta_i} \right)} \]  

(5)

where \( h_0(\eta \xi) \) is the surface roughness model based on polarized mode, \( \eta \xi \) is the polarized mode either in H and V, \( \sigma_{\eta \xi}^0 \) is backscattering coefficient on polarized mode, and \( \theta_i \) is the local incidence angle.

The fourth extracted data polarization roughness (\( h_0 \)) will be analyzed statistically using scatterplot for each ground truth data to see the correlation among variables as the summary in shown in Table 1. The medium to strong correlation between two variables is selected for primary and secondary data in multivariate estimation.

**Table 1.** The correlation between primary (ground truth) and secondary (satellite images) variables in each manifestation zones.

| Zone 1 | Suscep. | pH | Temp. | EC |
|--------|---------|----|-------|----|
| HH     | -0.29   | -0.52 | 0.35 | 0.57 |
| HV     | -0.28   | -0.59 | 0.44 | 0.32 |
| VH     | -0.28   | -0.51 | 0.35 | 0.23 |
| VV     | -0.35   | -0.50 | 0.35 | 0.56 |

| Zone 3 | Suscep. | pH | Temp. | EC |
|--------|---------|----|-------|----|
| HH     | -0.11   | -0.05 | -0.38 | -0.56 |
| HV     | -0.13   | -0.20 | -0.43 | -0.53 |
| VH     | -0.14   | -0.26 | -0.42 | -0.52 |
| VV     | -0.17   | -0.16 | -0.30 | -0.42 |

| Zone 2 | Suscep. | pH | Temp. | EC |
|--------|---------|----|-------|----|
| HH     | 0.29    | 0.10 | 0.28 | 0.11 |
| HV     | 0.39    | 0.31 | 0.27 | 0.10 |
| VH     | 0.42    | 0.36 | 0.22 | 0.02 |
| VV     | 0.29    | 0.36 | 0.19 | -0.09 |

| Zone 4 | Suscep. | pH | Temp. | EC |
|--------|---------|----|-------|----|
| HH     | -0.36   | -0.52 | 0.25 | 0.28 |
| HV     | -0.35   | -0.54 | 0.17 | 0.18 |
| VH     | -0.37   | -0.57 | 0.21 | 0.21 |
| VV     | -0.26   | -0.39 | 0.13 | 0.08 |

Note: the grey colour shows medium to strong correlation used for multivariate estimation.

Ground truth data measurement is not spread evenly across the surface, but the pattern is clustering based on the location of geothermal manifestations. The distance between two data point is about 30 m referred to the pixels size on radar images. Therefore one data point represents one data ground truth of roughness in the image. Prior to estimation, the data is grouped by spaces to reduce the error when data is analysed together.

4. Results and Discussion
During the first stage of exploratory data analysis, the data distribution is described using descriptive statistics in each zone with the summary is shown in Table 2.

**Table 2.** Statistical summary of sample data (ground truth and roughness) for Zones 1 to 4.

| Zone 1 | Mean | Median | SD | Min | Max | RMSE |
|--------|------|--------|----|-----|-----|------|
| EC     | 1.36 | 0.06   | 4.71 | 0.01 | 20.00 | 5.87 |
| pH     | 6.51 | 6.8    | 0.89 | 4.05 | 7.48 | 0.96 |
| Suscep.| 4.06 | 4.03   | 3.68 | 0.02 | 15.95 | 2.92 |
| Temp.  | 23.14 | 15.70 | 20.72 | 13.80 | 93 | 25.06 |
| HH     | 6.84 | 5.37   | 3.50 | 1.95 | 18.33 | - |
| HV     | 7.03 | 6.49   | 2.54 | 1.95 | 15.13 | - |
| VH     | 8.35 | 7.69   | 3.17 | 1.95 | 18.45 | - |
| VV     | 6.05 | 4.66   | 2.90 | 1.95 | 15.27 | - |
### Zone 2

|     | Mean | Median | SD  | Min  | Max  | RMSE |
|-----|------|--------|-----|------|------|------|
| EC  | 0.14 | 0.11   | 0.11| 0.02 | 0.44 | 0.13 |
| pH  | 6.92 | 6.94   | 0.36| 6.28 | 7.92 | 0.39 |
| Suscep. | 3.53 | 3.57   | 1.12| 1.26 | 5.59 | 1.03 |
| Temp. | 18.61| 19.3  | 2.40| 14.00| 22.40| 2.90 |
| HH  | 5.09 | 5.06   | 0.55| 3.85 | 6.66 | -    |
| HV  | 6.20 | 6.16   | 0.81| 4.42 | 8.10 | -    |
| VH  | 7.34 | 7.19   | 1.10| 5.19 | 10.28| -    |
| VV  | 4.69 | 4.61   | 0.50| 3.76 | 6.59 | -    |

EC: Electric Conductivity (ms); pH, Suscep., Temp., HH, HV, VH, VV: Roughness extracted from radar data (cm).

The result of estimation using COK method is shown in Figure 4. In Zone 1, we can see that all physical parameters reveal the heterogeneous occurred in NS - SW direction. It can be concluded that there is a good correlation among parameters within the Zone 1. In S - W direction, the estimated temperature is high; the ground truth shows that this area is Kawah Burung, the crater valley, while the temperature is decreasing toward the N - S direction. When we compared with the electric conductivity (Figure 4a; Zone 1), it shows the same colour pattern means that it is correlated to the temperature. But the pH (Figure 4b; Zone 1) and susceptibility (Figure 4d; Zone 1) has a reversed pattern and it can be concluded that both of parameters were inversely correlated. The same pattern also occurs in Zone 4.

The parameters from estimation results are more difficult identified at manifestations of Zone 2. Colour pattern almost has no resemblance in this zone. The correlation among physical parameters within the Zone 2 has low correlation.

The characteristic of physical parameters from the estimation in Zone 3 is unique. The pattern of colour for all estimates almost shows similar results. This indicates that all parameters linearly correlated. This phenomenon did not occur in the Zones 1 and 4. Theoretically, the increasing temperature would reduce the magnitude of magnetization (susceptibility) material. Using ground truth data, Zone 3 around the springs Cibolang shows temperature about 67.7°C and pH 6.75. The pH should be low because of the present of acidic nature of water. The pH has possibility to be high due to the influence of surface water. Further study related to this phenomenon is indispensable. Zones 1 and 4 have similar physical properties which are located in the fracture zone that related directly to the geothermal reservoir.
The Root Mean Square Error (RMSE) of the estimation results is similar to the standard deviation of data as shown in Table 2. The use of COK method is appropriate to characterize the physical parameters of surface manifestation within geothermal area. Validation using scatterplot for the estimation of measurement data is also performed, but the correlation is less good. The correlation between measurements data and radar image data is also less dominant.
5. Conclusion
The characteristics of natural physical parameters could be estimated using Cokriging method (COK) which showed respectable estimation. In general, the characteristic of Temperature had positive linear correlation with the Electric Conductivity (EC), and has negative correlation with pH and Susceptibility. The unique characteristics occurred in Zone 3 where all parameters had positive linear correlation, and we need further study to know well about this phenomenon. Zones 1 and 4 have similar physical properties and they are located in fractures zone which is directly related to the geothermal reservoir.

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References
[1] Wackernagel H.: Multivariate Geostatistics: An Introduction with Applications. Springer-Verlag Berlin Heidelberg, New York, 1995.
[2] Hochstein M.P. and Sudarman S.: History of Geothermal Exploration in Indonesia from 1970 to 2000. Geothermics 37, 2008, 220-266.
[3] Purnanto M H and Purwakusumah A.: Fifteen Years (Mid-Life) of Wayang Windu. Proceedings World Geothermal Congress 2015. Australia: Melbourne.
[4] Alzwar M., Akbar N. and Bachri S.: Geological Map of the Garut and Pamengpeuk Quadrangle, Jawa. 2nd edition, Geological, Research and Development Center. Indonesia, 2004.
[5] Bogie I., Kusumah Y.I. and Wisnandary, M.C.: Overview of the Wayang Windu Geothermal Field, West Java, Indonesia. Geothermics. vol. 37, 2008, pp. 347-365.
[6] Yalçin E.: Cokriging and its effect on the estimation precision. The Journal of The South African Institute of Mining and Metallurgy. Volume 105, April 2005.
[7] Minnitt R.C.A. and Deutsch C.V.: Cokriging for optimal mineral resource estimates in mining operations. The Journal of The Southern African Institute of Mining and Metallurgy. Volume: 114, March 2014.
[8] Meilianda E, Huhn K, Alfian D and Bartholoma A.: Application of Multivariate Geostatistics to Investigate the Surface Sediment Distribution of the High-Energy and Shallow Sandy Spiekeroog Shelf at the German Bight, Southern North Sea. Scientific Research: Open Journal of Marine Science, 2, 2012, 103-118.
[9] Saepuloh A., Urai M, Sumintadjireja P and Suryantini: Spatial Priority Assessment of Geothermal Potentials Using Multi-Sensor Remote Sensing Data And Applications. Proceedings, 1st ITB Geothermal Workshop 2012. Institut Teknologi Bandung, Bandung, Indonesia. March 6-8, 2012.
[10] Saepuloh, A., Koike, K., Urai, M., and Sri Sumantyo, J.T.: Identifying surface materials on an active volcano by deriving dielectric permittivity from polarimetric SAR data, IEEE Geoscience and Remote Sensing Letters (GRSL), 12(8), 2015, 1620-1624.