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Geomorphic Indices Characteristics Related to Geothermal Manifestation Appearance and 3D Modelling Micromine Software in Wayang Windu Geothermal Field

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Abstract— *The research site is administratively located in Bandung Regency, West Java Province. This area had a unique morphology forming a horseshoe composed of Quaternary volcanic rocks which is a geothermal field. This study aimed to discover the relationship between geomorphic index characteristics to the geothermal manifestation appearance in the research site through 3D modelling using micromine software. The results of the geological lineament analysis were interpreted as geological structures trending west-east (W-E), northwest-southeast (NW-SE) and northeast-southwest (NE-SW). Geomorphic index characteristics showing active tectonic class (S_{mf} value: 1,34 – 1,99) and medium (S_{mf} value: 2,06 – 2,41), medium lineament density (L_d value: 1,013 – 1,229 km/km²), and height (L_d value: 1,229 – 1,900 km/km²). 3D modeling using micromine software clearly showed the continuity of geological structures on the surface to the subsurface. The accumulation facilitated geothermal fluids from beneath the surface to move and emerge on the surface as geothermal manifestations. The spread of geothermal manifestations can be divided into three groups, which are: TKR-1 group (Sub-watershed CTR-2, CTR-4, CLK-3, and CLK-4). TKR-2 group (sub-watershed CTR-3, CLK1, and CLK-2), TKR-3 group (sub- watershed CTR-1 and CLK-5).*

Keywords— *Geological Lineament, Geomorphic Indices, Geothermal Mantifestations, Micromine, Wayang Windu.*

I. INTRODUCTION

West Java is a province which produces the largest geothermal energy with six existing PLTPs, in the amount of 1194 Mega Watt (MW) from 2130,7 MW or 56% of the electricity from existing PLTPs in Indonesia. According to the national geothermal road map, in 2025 around 39,5% of its development is located in West Java. The total potential of geothermal resources is 2159 MW and the total potential of reserves is 3765 MW, and the total of both are 5924 MW (Mahlia, 2016). One of the geothermal fields in West Java which has been operating is the Wayang Windu geothermal field. This field is a geothermal producer that has contributed 227 MW of geothermal energy with unit 1 producing 110 MW and unit 2 producing 117 MW. The two generating units are supported by a number of production wells (Star Energy Geothermal, 2022).

A quantitative approach by calculating several geomorphic indices (morphotectonic) variables in a watershed on the data from geological and topographic lineament analysis. The analysis results of the Geomorphic Indices value are able to determine its relationship to the geothermal manifestations appearance in the Wayang Windu geothermal field (Fig 1) and visualized in three dimensions (3D) by applying the Micromine software, so that it can visualize the relationship between the Geomorphic Indices characteristics and the geothermal manifestations appearance which are also related to the presence of wells in the research site.

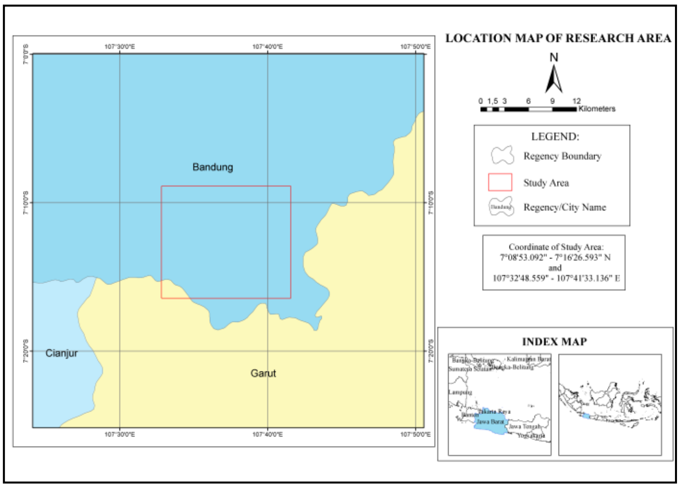

Fig. 1. Research area located on Bandung Regency, West Java province, Indonesia.

II. METHOD

This study was carried out in several stages, such as preparatory stage, inventory of data related to research objects consisting of geology and geomorphology aspects, as well as information about watersheds in the research site. Zoning the watershed into several sub-watersheds was also conducted in order to analyze its morphotectonic aspects.

The data tabulation and analysis were related to the geological structure lineament and the morphotectonic aspects of watersheds such as the mountain front sinuosity (S_{mf}) and the lineament density (L_d).

A. Structure Lineament

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The geological structure lineaments in the form of a ridge could determine the extent to which it is deformed in an area (Sukiyah, 1993). The geological structure lineament including ridges and valleys as well as river flows were analyzed based on data from the Citra Shuttle Radar Topography Mission-Digital Elevation Model (SRTM-DEM). The results of lineament analysis would be presented in a rosette diagram to discover the existing level of lineament intensity.

B. Mountain front sinuosity (S_{mf})

Mountain front sinuosity (S_{mf}) described the stability between erosion and tectonic which form the mountain front which coincide with fault boundaries or existing structures (Doornkamp, 1986 in Gentana, 2018).

S_{mf} calculation utilized the equation (1) (Keller and Pinter 1996):

$$S_{mf} = Lmf / Ls \qquad (1)$$

Lmf: length of mountain front segment
Ls: length of projected mountain front segment
Based on the calculation of S_{mf} will result the figures that can be interpretated according to the classification on Table 1.

TABLE 1. The classification of S_{mf} value and related to the active tectonic levels (Doornkamp,1986 in Gentana, 2018)

S_{mf} Value	Tectonic Activity
1.2 – 1.6	Active
1.8 – 3.4	Active moderate
2.0 – 5.0	Low

C. Lineament density (L_d)

Lineament density values (L_d) illustrated the lineament density value aligned with the permeability conditions below the surface. High lineament density values indicate high density anomalous areas and potential permeable zones associated with geothermal reservoirs which cause geothermal fluids to move vertically or laterally to the surface (Soengkono, 1999). L_d calculation utilized the equation (2) (Soengkono, 1999):

$$L_d = F/A \qquad (2)$$

F: Lineament Frequency (Km)
A: Area calculation (Km^2)

III. RESULT AND DISCUSSION

A. Regional Research Area

The Wayang Windu Geothermal Field is located on the southern slopes of Mount Malabar (a large andesitic stratovolcano) and a sequence of smaller volcanoes which extend southward, including Mount Bedil, Mount Wayang, and Mount Windu (Bogie and Mackenzie, 1998). On the regional geological map sheets of Garut and Pameungpeuk (Alzwar, et al., 1992), the Kencana Unit is interpreted to be equivalent to the Waringin-Bedil Andesite unit, Old Malabar (Qwb) which are Early Pleistocene age and the Kencana lava unit (Qkl) and Huyung lava (Qhl) which are Late Pleistocene age. The Kendang unit is equivalent to the Early Pleistocene Guntur-Pangkalan and Kendang Volcano rock units (Qgpk). The Malabar unit is equivalent to the Late Pleistocene Malabar-Tilu (Qmt) volcanic rocks unit and the old undecomposed volcanic loose spice deposit (Qopu). The Wayang-Windu unit is equivalent to young volcanic rocks (Qyw) of Holocene age (Fig 2).

The research area is included in the magmatic arc represented by active volcanic lines along the axis of Java Island. The geological structure in this area is estimated to originate from the north-south (U-S) trending pressure produced by the subduction process of the Indian Ocean Plate with the Eurasian Continental Plate (Alzwar, et al., 1992) (Fig 3). Mount Malabar is located in the Sunda Quaternary arc which was formed as a result of the subduction of the two plates. Mount Malabar is a Quaternary Volcano located on the southern boundary of the Bandung Intramontane Basin (Van Bemmelen, 1949).

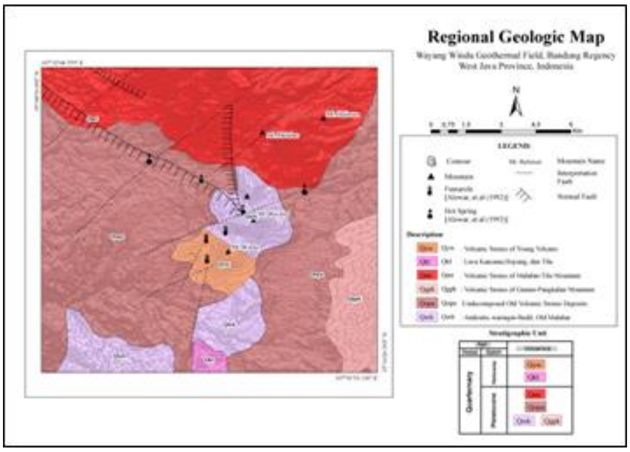

Fig. 2. Regional Geologic Map sheet location of research area.

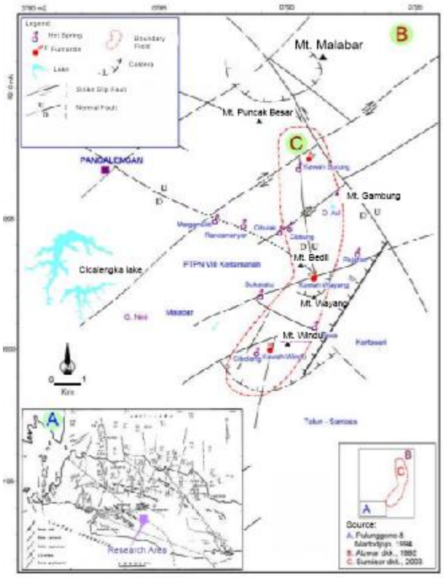

Fig. 3. Geological Structure Map

B. Geothermal Manifestation of Research Area

The geothermal system in the Wayang Windu area is depicted in the conceptual geology of the geothermal system which consists of a cap zone, reservoir zone, reservoir fluid, reservoir temperature, heat source, geothermal manifestation, up-flow zone, outflow zone, and recharge zone (Fig 4). The Wayang Windu field has two phases dominated by vapor, which are influenced by areas dominated by liquid (Mulyadi, 2011). The reservoir zone which located in the up-flow zone (Gunung Wayang) acts as the parent fluid which subsequently the fluid from the zone separated into a vapor phase and a liquid phase through a boiling process at temperatures above 221ºC. The liquid phase derives from the fluid in the up-flow zone which flows into the outflow zone (Mount Gambung), in the flowing fluid process from the up-flow zone to the outflow zone it undergoes a mixing process with meteoric water which has been heated in depth at a temperature of 220ºC. While the vapor phase comes from the fluid in the up-flow zone which flows into the outflow zone (Mount Bedil), the fluid is also diverse with shallower meteoric water yet at a temperature of 250ºC, this higher temperature causes the vapor phase to occur in the outflow zone at Mount Bedil (Fajar, 2005) (Fig 4).

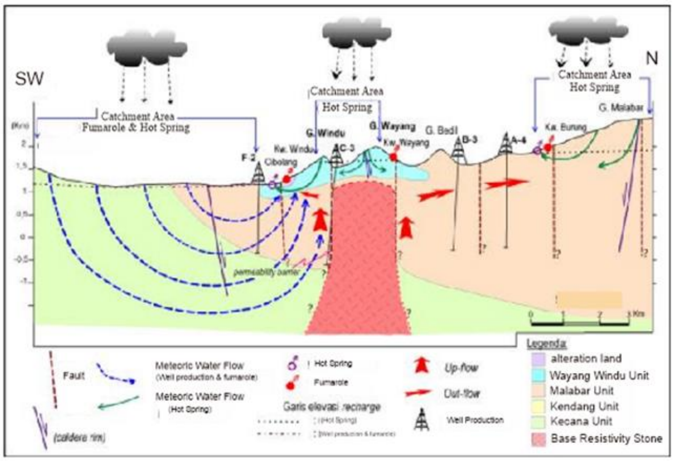

Fig. 4. Hydrogeological cross-section of Wayang Windu geothermal field (Fajar, 2005)

C. Watershed and Sub-Watershed Delination

The research site was located in the Citarum and Cilaki watersheds. In this study, Citarum watershed is divided into 4 sub-watersheds such as CTR-1 to CTR-4 and Cilaki watershed is divided into 5 sub-watersheds, such as CLK-1 to CLK-5. (Fig 5).

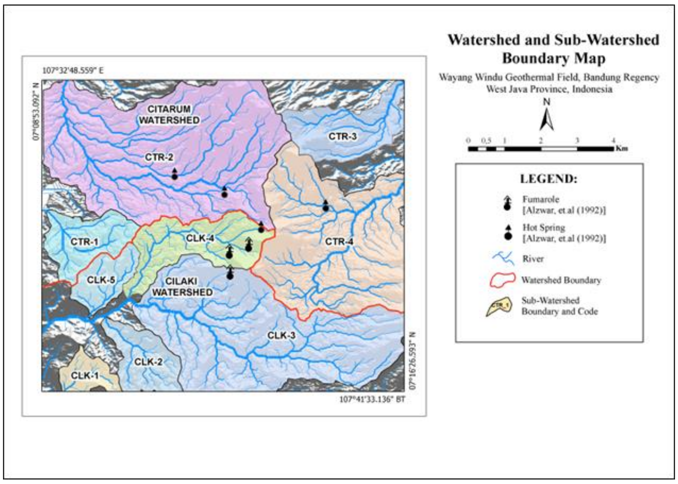

Fig. 5. Research area located in Citarum dan Cilaki watershed, delineated into nine sub-watersheds.

D. Geological Lineament Pattern

The Geological Lineament data (ridges and troughs) which tabulated produces a rosette diagram indicating the dominance of the geological lineaments trending northeast-southwest (NE-SW), northwest-southeast (NW-SE) and dominated by lineaments trending west-east (W–E). This lineament pattern undifferentiated from the regional structure pattern of Java Island, while the interpretation results of previous researchers showed a geological lineament pattern trending northwest-southeast (NW–SE) called the Meratus pattern and pattern trending northeast-southwest (NE-SW) called the Sumatra pattern. The faults and geological structures in the research site were complex in the central to upper (north) and northwestern parts of the area (Fig 6).

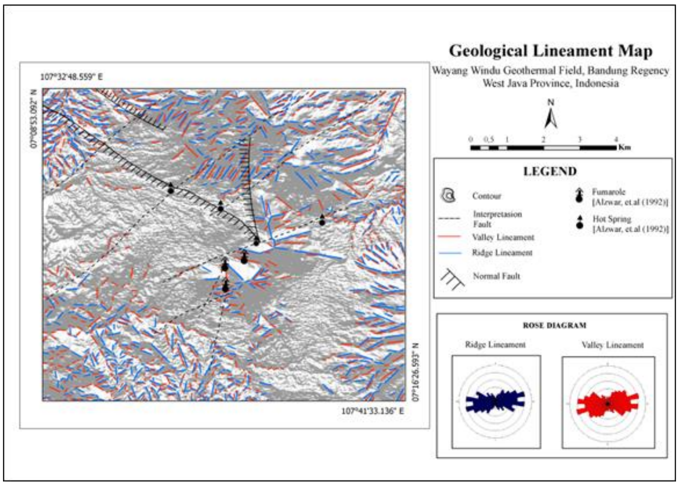

Fig. 6. Ridge and valley lineament map show main lineament pattern is northwest – southeast (NW - SE) orientation.

E. Geomorphic Index: Mount Front Sinousity (S_{mf})

The study of the mountain front sinousity was carried out on 10 segments spread over various points in a relatively northeast-southwest direction. Each segment was formed by solid straight lines (Ls) and lines that follow contours (S_{mf}).

The results of the research on the mountain front sinuosity were carried out on ten segments spread over various points in a relatively northeast-southwest direction, with a S_{mf} value range of 1,58 – 3,66 (Table 2). The value of the analysis results refers to the tectonic classification of Keller and Pinter (1996), indicating that this area has three tectonic classes such as active tectonic class (represented by a red line segment), medium tectonic class (represented by a yellow line segment), and inactive tectonic class (represented by a colored line segment green) (Fig 7).

Four hot springs and three fumaroles closely emerged to several S_{mf} segments including segments 1,3 and 5 with active tectonic values. This showed that the manifestations appearance involving hot springs and fumaroles in the research site was greatly influenced by tectonic activity based on the indices of mountain front sinuosity.

TABLE 2. Mount Front Sinousity (S_{mf}) calculation result in research area

Mount Front Segment	Lmf (km)	Ls (km)	S_{mf}	Tectonic Activity
1	5,65	3,57	1,58	Active
2	4,41	1,82	2,41	Active Moderate
3	7,26	3,63	1,99	Active
4	6,51	4,03	1,61	Active
5	4,04	3,23	1,24	Active
6	8,97	4,24	2,11	Active Moderate
7	8,63	2,35	3,66	Low
8	3,08	2,29	1,34	Active
9	5,13	2,39	2,14	Active Moderate
10	3,87	1,87	2,06	Active Moderate

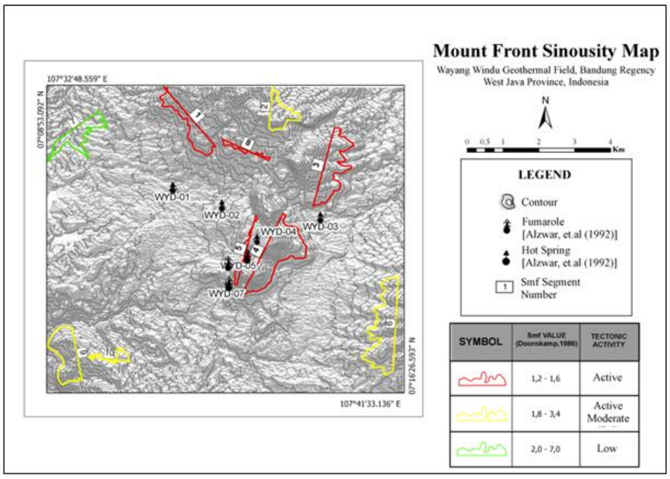

Fig. 7. Sinuosity Mount Front (S_{mf}) map show three class of tectonic activities are active,active moderate and low.

F. Geomorphic Index: Lineament Density (L_d)

The tabulated results of the lineament density (L_d) of the research site (Fig 8) showed six colors which were classified into three intensity density zones, such as low, medium and high intensity zones. Zones with low intensity have an L_d value range of 0 – 0.618 km/km², zones with moderate intensity have an Ld value range of 0.618 – 1.013 km/km², and high intensity zones have an L_d value range of 1.013 – 1.900km/km². The intensity of lineament density zones was categorized based on Soengkono's 1999 classification which is adjusted according to the order of L_d values from lowest to highest in the research site.

The results of high L_d values reflect subsurface conditions that have high rock permeability as well and indicate potential permeable zones that can be associated with geothermal reservoirs (Soengkono, 1999). This can be proven by the geothermal manifestation appearance in the research site which emerge in zones with moderate to high lineament intensity. The appearance of geothermal manifestations was also caused by faults or fissures that continue beneath the surface which causes hot fluid from the reservoir to rise and appear on the surface. as a manifestation of geothermal heat

The results of lineament density map analysis and general manifestations appearance of hot springs did not emerge in areas of high lineament density (high rock permeability) while fumaroles emerge in areas of high lineament density.

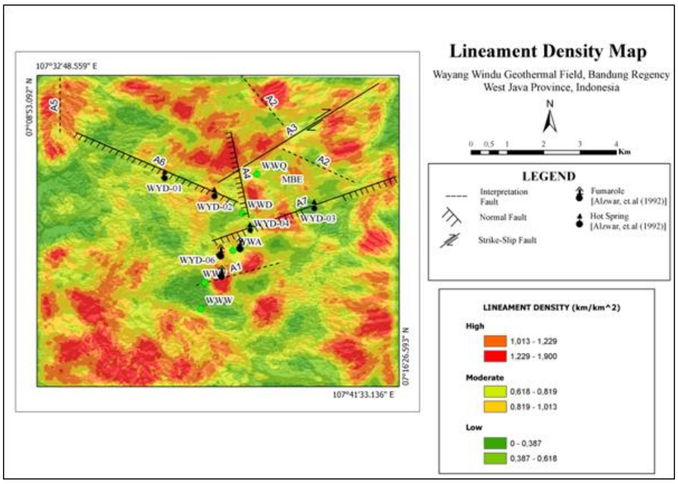

Fig. 8. Lineament density map (L_d) map show research area has low – high lineament density value

G. 3D Modelling Micromine Software

The formation of fault lines is the target of drilling geothermal wells both in terms of exploration and production, where these fault lines were useful as geothermal fluid circulation paths. In the 2D and 3D modelling of the Micromine software (Fig 9), it can be seen that the fault lines or planes were located in areas having a high level of permeability, geothermal manifestations that emerge to the surface were also located on the edges and intersections of the fault lines.

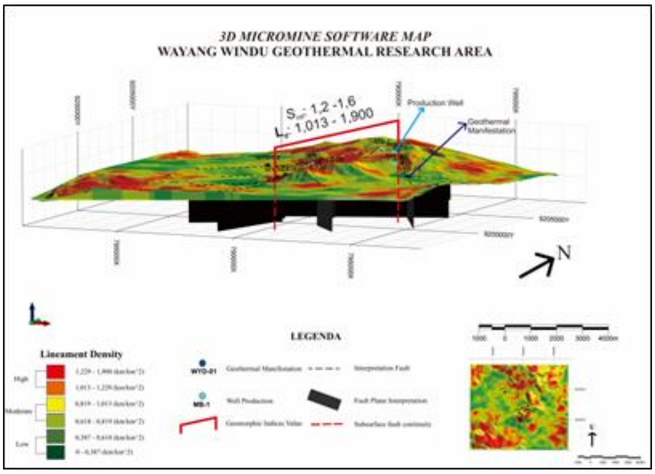

Fig. 9. Overlay geomorphic indices with 3D modelling Micromine Software

H. Geomorphic Indices Characterization Related to Manifestation Appearance in Research Area

The analysis of the geomorphic indices characteristics and analysis of the geological lineament patterns along with the geological structures in the research site were related to each other and showed their correlation to the geothermal manifestations appearance. The results of the Geomorphic indices analysis of the research site indicated that the research site has been influenced by mildly active tectonic activity (S_{mf} value: 1.24 - 2.41) in the research site, and had a moderate to high level of permeability (L_d value: 0.618 - 1.9 km/km^2).

The analysis of the geological lineament in the research site indicated that it had a northeast-southwest (NE-SW), northwest-southeast (NW-SE) pattern and was dominated by a west-east (W-E) trending pattern. The developed geological lineament structure pattern was estimated to be the result of active tectonics and causes deformation of the rock bodies hence created weak areas that become permeability zones resulting in the escape of geothermal fluid to the surface from a geothermal system reservoir.

The combined analysis results of the Geomorphic Indices and lineaments as well as the geological structure on the combined Geomorphic Indices characteristic map (Fig 10) showed the diversity of characteristics of each sub-watershed in the research area. Several existing sub-watersheds were not traversed by faults or geological structures, mountain front segments, and there were no geothermal manifestations and their production wells. Based on the results of the combined analysis, the research site was divided into three sub-watershed groups based on the level of potential for manifestations appearance, such as TKR-1 (red), TKR-2 (orange), and TKR-3 (green) (Table 3) (Fig 10).

The TKR-1 sub-watershed group is a group that had a potential for geothermal manifestations compared to other groups. The analysis results of the sub-watershed in the TKR-1 group indicated that it had an active tectonic level which causes a high level of permeability in the sub-watershed area where there were faults or geological structures, thus, they could support the appearance of geothermal manifestations to the surface.

TABLE 3. Hot spring groups based on geomorphic indices characterization.

Group	Sub-Watershed	L_d Value (km/km^2)	S_{mf} Value	Geothermal Manifestation
TKR-1	CTR-2	0,38-1,90 (Low-High)	1,34-3,66 (Active Tectonic)	Hot Springs WYD-01 and WYD-02
	CTR-4	0,38-1,90 (Low-High)	1,61-1,99 (Active Tectonic)	Hot Springs WYD-03
	CLK-3	0,38-1,90 (Low-High)	1,61 (Active Tectonic)	Fumarole WYD-07
	CLK-4	0,38-1,90 (Low-High)	1,24 (Active Tectonic)	Hot Springs WYD-04, Fumarole WYD-05 and WYD -06;
TKR-2	CTR-3	0,38-1,90 (Low-High)	1,99 (Active Tectonic)	-
	CLK-1	0,61-1,90 (Moderate-High)	2,14 (Moderate Active Tectonic)	-
	CLK-2	0,61-1,90 (Moderate-High)	2,06 (Moderate Active Tectonic)	-
TKR-3	CTR-1	0,38-1,01 (Low-Moderate)	-	-
	CLK-5	0,38-1,90 (Low-High)	-	-

The TKR-2 sub-watershed group is a group with slight potential for geothermal manifestations appearance as it had an active and moderate tectonic level and also had a high level of permeability in the sub-watershed area. The presence of faults or geological structures in this sub-watershed was merely discovered in several sub-watersheds and there was no appearance of geothermal manifestations in this sub-watershed group.

The TKR-3 sub-watershed group is a group with the lowest potential for geothermal manifestations of all existing groups. This was proven by analysis values showing that the sub-watersheds in this group had a relatively moderate to low level of permeability and there were no faults or geological structures in the area.

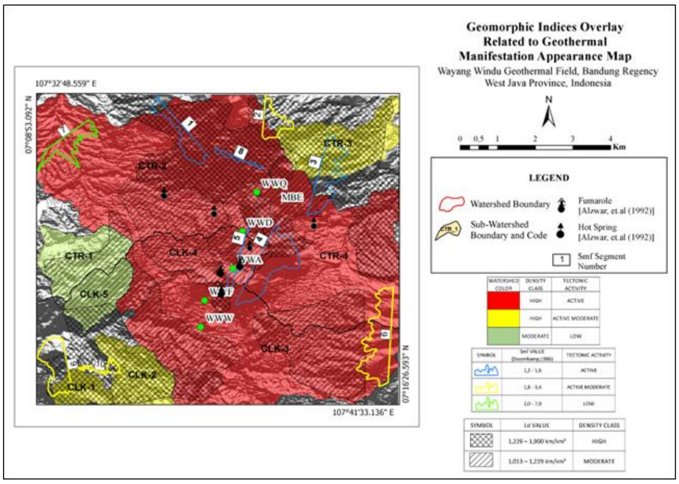

Fig. 10. Overlays map of two geomorphic indices; lineament density (L_d), mount front sinuosity (S_{mf}) show the appearance of geothermal manifestation located on area with low – high lineament density and active tectonic activity.

IV. CONCLUSION

Based on the geological lineament and five geomorphic indices analysis (L_d and S_{mf}) on SRTM-DEM map and SHP data, it can be concluded:

1. The pattern of geological lineament in the research area was west-east (W-E), northwest-southeast (NW-SW) and northeast-southwest (NE-SW).
2. The Geomorphic Indices characteristics based on the morphotectonic aspect showed that the research area has an active tectonic class (S_{mf} value: 1.24-1.99), medium to weak (S_{mf} value: 3.66), low lineament density (L_d value: 0, 00-0.618 km-1), medium (L_d value: 0.618-1.013 km-1), and high (L_d value: 1.013-1.900 km-1).

   The distribution of geothermal manifestations in the research area was based on the geological lineament pattern associated with the geological structure and the Geomorphic Indices characteristics and also supported by the location of existing production wells. The research site was divided into three sub-watershed groups, such as TKR-1, TKR-2, and TKR-3.
3. 3D modelling of the research area using the Micromine software depicted the fault lines on the surface becoming fault planes below the surface. The appearance of geothermal manifestations and the location of the wells were proven to be on the fault lines and edges on the surface.

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