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NON-LINEAR LINEAMENT DENSITY IMPACTS ON GROUNDWATER INFRASTRUCTURE FOR DROUGHT RESILIENCE IN KULON PROGO, INDONESIA

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Abstract

Drought poses a significant threat to water supply in regions like Kulon Progo, Indonesia. Seasonal water shortages lead to agricultural losses and increased disaster vulnerability. This study aims to improve groundwater exploration method for drought mitigation by analyzing the correlation between lineament density and groundwater using a dataset of 127 observations from Samigaluh and Kalibawang subdistricts using Pearson Correlation. The research uncovers a non-linear threshold at 4 km/km². Below the threshold, groundwater occurrence increases with density (r = 0.949), shows increasing infiltration. But above the threshold, occurrence decreases (r = -1.000), suggesting over-fracturing reduces storability. Maximum depths follow a similar pattern (r = 0.883 below, r = -1.000 above). These findings challenge conventional scoring methods in groundwater potential zoning, which often assume a linear positive relationship with lineament density. The study provides a novel framework for targeted exploration, prioritizing moderate-density zones to mitigate drought impacts and build resilience against climate-induced disasters.

Keywords: *Fracture, Groundwater, Lineament Density, Non-Linear Correlation*

1. INTRODUCTION

Drought is a condition when a place or an area is having a prolonged shortage of water supply (Douville, et al., 2021; Mulya, et al., 2024). Adding to that, climate change might worsen the upcoming drought whether increase in frequency or duration. In those drought prone areas, groundwater is a vital water sources for living. As such, a good groundwater exploration method is necessary for mitigation (Pappaka, et al., 2025; Sarastika, et al., 2025; Wahyuni, et al., 2024). If the water supply could be increased, then an area will no longer in state of drought.

Kalibawang and Samigaluh District in Kulon Progo Regency, Special Region of Yogyakarta, is one of many droughts' prone areas in Indonesia with limited water resources facility that could worsen the drought (Ikhsan, et al., 2024). Even though a lot of spring were found, it is insufficient for the resident living in those areas. At the peak of dry season, Regional Disaster Management Agency (BPBD) would need to send water to those areas regularly, just like in any other location. In aspect of geology and hydrogeology, the majority of both subdistrict have poor aquifer and even some regions without exploitable groundwater (Hendrayana & Ramadhika, 2016; Ministry of Energy & Mineral Resources, 2024). Fig. 1 shows the map of groundwater productivity as reported by the Ministry of Energy and Mineral Resources (2024).

Conventional method of groundwater exploration often employs multi criteria decision analysis (MCDA), especially Analytical Hierarchy Process (AHP) (Meng, et al., 2024; Shabani, et al., 2022; Tahera-Tun-Humayra, et al., 2025). AHP method still a popular method even to this day thanks to its simplicity and effectiveness at scoring different parameters relatively. Adding to that, it could be integrated into spatial analysis using GIS and remote sensing easily (Agogue Feujio, et al., 2024).

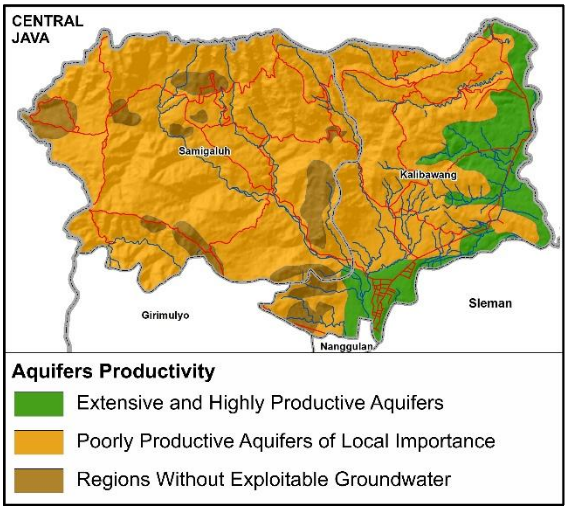

Fig. 1. Groundwater Productivity Map (Ministry of Energy and Mineral Resources, 2024)

One of the most used parameters in groundwater exploration is lineament density. The common assumption employed when using lineament density is the higher the density, the higher the potential as the permeability is increasing (Alemu, et al., 2025; Melese & Belay, 2022; Multaniya, et al., 2024). However, a linear assumption may overlook a factor that an excessive fracturing might lead to weathering in which the crack will be filled with mud or clay sized particle which clog the groundwater passage. On the other hand, excessive crack also poses a possibility of groundwater passage which to good than needed and made the groundwater flow rapidly. Rather than storing the water as supply, it became a simple drainage (Sander, 2007).

The aim of the research is to improve the groundwater exploration method for drought mitigation. The objective of the research was to quantify correlation between lineament density and groundwater occurrence.

2. METHODOLOGY

Dataset that was used in this research was limited to lineament density analysis and groundwater measurement data. Lineament density was extracted by using topographic data released by Geospatial Information Agency of Republic of Indonesia with data scale of 1:25.000. The recommended pixel size used for the scale is 12,5 meters (Hengl, 2006). The lineament extraction went through 3 process which are edge detection, thresholding, and curve extraction (Salui, 2018).

Extracted lineament will be processed further by using kernel density to obtain lineament density data. Kernel Density was chosen over line density methods for its method of quadratic kernel function. The quadratic kernel function could produce a better and smoother zonation and reduce any isolated line distribution that might be found in fractured volcanic area. On the other hand, line density would create a value of uniform averaging within an area. This method could result in the zonation kind of underperformed (Silverman, 1986).

Groundwater data was obtained through field survey in the peak of dry season. The peak of dry season was chosen to make sure that any groundwater data that was found with depth less than 1 meter really is groundwater data, not a surface water nor runoff (Damiba, et al., 2020). The groundwater data would be overlaid with lineament density data to obtain the correlation of both parameters.

The aim of this research is to study about the correlation of lineament density and groundwater occurrence that commonly used as parameter in AHP. As such, no lithology or any other parameters will be used.

Pearson formula (equation 1) was used in this research because it could quantify the strength and direction of linear relationship between parameters. It also can be used to identify trends in hydrogeological data (Berman, 2016; Xu, et al., 2024).

$$r = \frac{\sum(xi-\ddot{x})(yi-\dot{y})}{\sqrt{\sum(xi-\ddot{x})^{w}\sum(yi-\dot{y})^{2}}} \quad (1)$$

Where :
r = relation coefficient
xi = value of x in sample
ẍ = average value of x
yi = value of y in sample
ỳ = average value of y

The range of Pearson Correlation value (r) is from -1 to 1. The closer the value to 1 or -1, the more linear it is. The closer the value to 0, the less linear it is. It also shows whether the correlation is positive or negative.

2.1 Data Reuse Statement

Part of the groundwater dataset used in this study was also analyzed in two earlier publications by the author. The first (Susatio, et al., 2025a) evaluated interpolation methods for groundwater depth and elevation, while the second (Susatio, et al., 2025b) examined groundwater's influence on landslide susceptibility. In this study, the same field dataset is reinterpreted together with newly extracted lineament density data to analyze non-linear groundwater–lineament relationships in the context of drought-resilient groundwater exploration. The reuse is limited to the dataset only; no duplication of analysis, figures, or text has been conducted.

3. RESULT AND DISCUSSION

3.1 RESULT

Kernel density analysis produced lineament density of 0 to 6.1525 per km^2 (Fig. 2). Most lineament can be found in Samigaluh area while Kalibawang Subdistrict area has less. For the groundwater data, this research used 127 observation point that was found through Kalibawang and Samigaluh Subdistrict. Based on the overlaid data, most groundwater can be found in Kalibawang area which has less lineament as shown in Fig. 2. In this research, the correlation was divided into two section, groundwater occurrence and groundwater depth.

Data that being used for the groundwater occurrence is the presence of the groundwater source. On this part, the depth is ignored. Groundwater occurrence and lineament density data is being classified into 6 class with no groundwater found in lineament density of more than 6 km/km^2 (Table 1).

As shown in Table 1, groundwater occurrence increased as the lineament density getting higher. But the groundwater occurrence is decreasing significantly when the density reached some point. If we use all data and calculate the correlation using Pearson Formula, the value is -0.517. The minus value showed there is decline in sites as density increases. Value of 0.5 showed that the trend and correlation is relatively weak. By the data, we can conclude that at some threshold the correlation is being reversed.

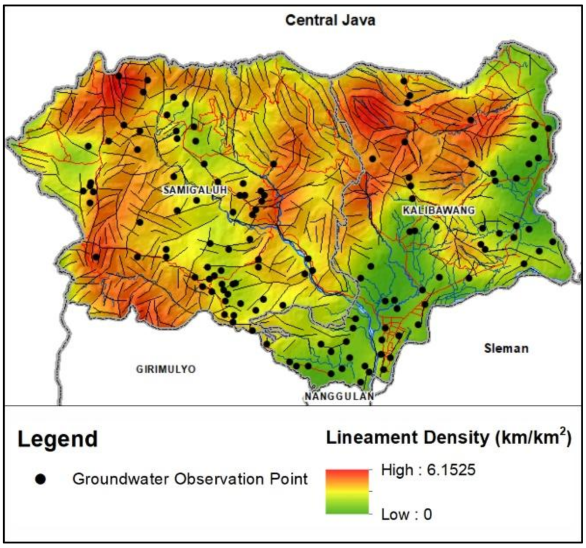

Fig. 2. Lineament Density Map

Table 1. Groundwater Occurrence on Lineament Density

Density (km/km^2)	Sum of Groundwater Observation Point
0-1	19
>1 – 2	28
>2 – 3	28
>3 – 4	37
>4 – 5	13
>5 – 6	2

To get a better comprehension, a threshold is necessary to divide the data. By putting the threshold on 4 km/km^2, the Pearson correlation increased significantly. For the correlation below threshold of 4 km/km^2, Lineament density and groundwater occurrence has Pearson value of 0.949 which indicate strongly positive. The correlation below threshold is in line with previous research that stated groundwater occurrence increase with lineament density (Dongare, 2024; Pappaka, et al., 2025; Sander, 2007). On the other hand, Pearson Correlation value of lineament density and groundwater occurrence is perfect negative (r = -1.000). It shows above threshold 4 km/km^2, the more lineament density an area has, the less groundwater can be found. This could be because of excessive permeability leading to water only flow through it and not being stored (Wu, et al., 2021). or the other possibility was the decrease of permeability because it was closed due to smaller fragments (Zhong & Leung, 2020)

Second correlation that was analyzed in this study is the groundwater depth. Each groundwater occurrence depth is plotted into scatter chart with lineament density as X axis and groundwater as Y axis as shown in Fig. 3. Maximum groundwater depth and lineament correlation would give an insight of vertical extent of the aquifers (Sultan, et al., 2010).

Groundwater depth also shows the same data distribution as groundwater occurrence. Groundwater depth would increase as the lineament density increase, but it dropped significantly at some threshold. The deepest groundwater can be found in lineament densities of > 3 to 4 km/km^2 which can be classified as moderate densities.

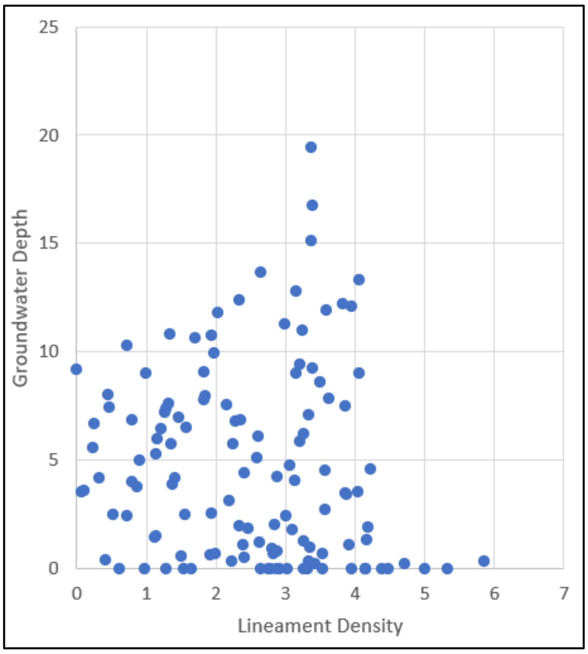

Fig. 3. Graph of Groundwater Depth and Lineament Density

Groundwater depth and lineament density Pearson Correlation value was way worse than groundwater occurrence. If all the data is being used without any threshold, the value was only -0.206. The low and negative value shows there's only a subtle correlation between lineament density and groundwater depth. But if threshold of 4 km/km^2 was applied, the correlation increased significantly. Groundwater depth and lineament density below threshold have Pearson Correlation value of 0.883. the positive and close to 1 value shows the higher lineament density found, the deeper the groundwater is (Olomo, et al., 2025). A deeper groundwater can be inferred as lineament managed to penetrate deeper in to the soil or existing materials in the research area. Above threshold 4 km/km^2 lineament density, just like groundwater occurrence, the Pearson Correlation value is -1. The value shows the higher the lineament, the shallower the groundwater depth which is practically a spring. Again, the possibility lies in too much fracture is just creating a way for water to flow, not store it, or it simply clogged (Wu, et al., 2021; Zhong & Leung, 2020).

Other than max depth, we also see the minimum and mean groundwater depth (Table 2). For the minimum depth, there's not much different for each class shows any lineament density could have a spring water. The mean depth of groundwater also similar to maximum depth. The value is increasing at the peak of class 3 to 4 km/km^2 and decreased above threshold of 4 km/km^2. The depth data indicate that at the high lineament density area, the only available groundwater sources were shallow or spring water.

Table 2. Groundwater Depth on Lineament Density

Density (km/km^2)	Max Depth	Min Depth	Mean Depth
0-1	19	0	3.85
>1 – 2	28	0	4.12
>2 – 3	28	0	4.78
>3 – 4	37	0	6.92
>4 – 5	13	0	4.56
>5 – 6	2	0.35	0.35

3.2 DISCUSSION

Result of this study gave a critical finding for the groundwater and lineament density correlation. This research found that the correlation between lineament density and groundwater was not a linear correlation, but non-linear. Most groundwater exploration research deemed high lineament density area as the best area with groundwater potential (Melese & Belay, 2022; Olomo, et al., 2025; Tahera-Tun-Humayra, et al., 2025). On the other hand, this research more aligned to non-linear perspective which believed in saturation points (Wu, et al., 2021; Zhong & Leung, 2020). As such, it can be said that the identified threshold or saturation point was at 4 km/km^2 where groundwater and lineament density correlation changed from linear to non-linear. At 4 km/km^2, the correlation shifted from increasing to decreasing with higher densities.

The threshold effect can be attributed to hydrogeological mechanism in which below 4 km/km^2 the lineament density facilitated interconnected fracture network that increase infiltration and storage (Melese & Belay, 2022; Olomo, et al., 2025; Tahera-Tun-Humayra, et al., 2025). Below threshold, the correlation shows a positive value of r = 0.949 for occurrence and r = 0.883 for max depth. This finding strengthens the concept of fracture-controlled aquifers where moderate lineaments increase infiltration with less leakage [0, 18, 19, 38]. However, above the threshold the correlation was having a reversal. Rather than increasing the groundwater potential, the lineament density decreased it. The reason lies in the possibility of create more flow path which lead to rapid drainage and reduced aquifer retention. As such, lineament density above 4 km/km^2 might be limiting groundwater storage (Wu, et al., 2021; Zhong & Leung, 2020).

This finding shows that conventional assumptions that being used for groundwater exploration might be wrong. This research invalidated common assumption if MCDA and AHP-based research that assign linear scoring where the higher the lineament density, the more groundwater can be found (Melese & Belay, 2022; Olomo, et al., 2025; Tahera-Tun-Humayra, et al., 2025).. The key point is most research in semi-arid areas chose to simplify or ignore the potential drawback of over-fracturing while this study shows it is an incorrect assumption (Wu, et al., 2021; Zhong & Leung, 2020).

By applying this finding, some area that previous research was assigned as high potential area could be changed into low or even not potential. It could have a significant implication toward drought mitigation. In Kulon Progo, if linear models were applied to solve the drought, the resulted zonation might lead to misguided exploration in high lineament density zones. As this study shows above the lineament threshold the groundwater occurrence became less and shallower, the exploration could potentially participate in worsening the drought vulnerability by directing efforts to less productive area (Rahman, et al., 2025; Tahasin, et al., 2024). It would be better to focus the exploration to area with moderate lineament density to tackle the drought problem.

For disaster mitigation, the result of this research suggested threshold analysis need to be included for regional planning. In Kulon Progo, drought could be linked to socioeconomic vulnerability. As such, focusing groundwater infrastructure on moderate lineament density could increase community resilience through sustainable wells. This approach also could reduce reliance on surface water that prone to evaporation during dry season and reduce the potential of soil erosion from surface water (Fender, et al., 2024). It also could be used to other disaster mitigation such as landslides as groundwater occurrence increase landslides hazard (Susatio, et al., 2025b).

Limitation in this research is the lack of temporal data. For the future research it would be better if the research integrates multi season and multi years groundwater data. Adding geophysical such as vertical electrical sounding methods could also increase the validity the research (Wilopo, et al., 2020, 2019).

4. CONCLUSION

This research highlighted the important effect of lineament density threshold effect on groundwater occurrence and depth in Samigaluh and Kalibawang Subdistrict, Kulon Progo. By showing that the correlation peaked below threshold of 4 km/km^2 and decreased significantly above the threshold, this research invalidated linear scoring in conventional groundwater exploration methods that ignore the risks of over fracturing.

This research also recommends mitigation planning to focus groundwater exploration on moderate lineament density rather than high lineament density. Prioritizing exploration on the high lineament density would be less effective or efficient as it has less groundwater. Adopting this non-linear approach could build long term resilience in drought prone area like those in Kulon Progon.

Future research should consider to spatiotemporal analyses which combine remote sensing with field validation to increase model accuracy.

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