The Comparison of Spatial Models in Peak Ground Acceleration (PGA) Study

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Abstract
This study was conducted to compare the performance of three different spatial analysis models: Inverse Distance Weighted (IDW), Ordinary Kriging, and Regularized Spline interpolation technique to determine the best fit model representing Peak Ground Acceleration (PGA) in West Java Province, Indonesia. The three models are commonly used in spatial visualization, but have different calculation methods. The calculations were performed using available formulas while the spatial modeling was conducted using the algorithms in GIS software. Meanwhile, the accuracy of the spatial model and factual calculation was determined through the Root Mean Square Error (RMSE). The results showed differences for both spatial distribution and maximum and minimum values for each model. However, IDW was observed to be the model which approaches the factual value of the PGA calculation as indicated by its RMSE value of 0.772352 in comparison with the 7.169879 (Ordinary Kriging) and 1.140802 (Regularized Spline).

1. Introduction

Indonesia is a tropical country clamped by three different plates - the Indo-Australian, Eurasian, and Pacific plates, thus, it is highly affected by catastrophic conditions of soil erosion, especially ones caused by rainfall and land use (Fulazzaky and Gany, 2009). The West Java Province was chosen as the research area due to its complex tectonic structure (Supendi et al., 2018) and high seismic activity due to volcanic and tectonic activities (Song et al., 2020 and Métaxian et al 2020). Moreover, West Java is one of the provinces heavily impacted by erosion (Cepeda et al., 2010). Meanwhile, the landslide vulnerability in Indonesia is caused by several factors such as lithology, geomorphology, land use, rainfall, and earthquakes (Ngadisih et al., 2016). These conditions allow spatial test models for geographical conditions and impact variables from the PGA in West Java.

Spatial modelling provides information infographic means and is usually obtained through algorithms available in some GIS softwares. The three models for this study are Inverse Distance Weighted (IDW), Ordinary Kriging, and Regularized Spline. The IDW interpolation is often used in different scientific fields such as geology because it is computation-intensive, well-documented, and easy to implement (Huang et al., 2011). Ordinary Kriging is a geostatistical interpolation approach consisting of several methods such as Indicator, Simple, Ordinary, and Co-Ordinary Kriging which are generally used in estimating spatial distribution (Belkhiri et al., 2020). Moreover, the Regularized Spline model is a type of interpolation from numerical data which has the ability to describe three-directional triangulations (Greoselj and Speleers, 2021). These three models are usually applied in geography, hydrology, and geology studies based on the location and several study parameters.

IDW and Ordinary Kriging have been compared in several studies such as Modeling Land Price Distribution in Wuhan, China (Hu et al., 2013), Estimating Groundwater Arsenic Concentration in Texas (Gong et al., 2014), Lineament Extraction and Analysis in Kulon Progo, Indonesia (Setianto and Triandin, 2013), Liquefaction Potential Over Alluvial Ground in Saitama, Japan (Pokhrel et al., 2013) and several others. Meanwhile, Regularized Spline interpolation model studies are usually adapted and modified into a new analysis as observed in the study of Spatial Pattern Analysis and Prediction of Forest Fire in Lao Cai, Vietnam (Bui et al., 2019). Each of these models has specific algorithms usually applied to describe non-spatial data into spatial data as well as certain advantages and disadvantages in analyzing a study. It is,

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however, important to note that accuracy and precision are very important to spatial studies. Peak Ground Acceleration (PGA) is an analysis to estimate ground vibrations in the prediction equation for ground motion through the concept of attenuation equations and also serves as an indicator of potential damage due to earthquakes (Gullu, 2012). The study of PGA is usually presented in a spatial form to ensure a more comprehensive understanding. It is related to magnitude, epicenter, epicenter location, and hypocenter depth leading to seismicity. The PGA study also has the ability to serve as the basis for the implementation of several studies such as Karst Collapse Susceptibility Mapping in section, The Attica Preture (Padopoulou-Vrynioti et al., 2013), Prehistoric Landslides in the Sea of Galilee, Dead Sea transform (Yagoda-Biran et al., 2010), Earthquake Rapid Response and Early Warning System in Istanbul (Wagener et al., 2016) and infrastructure development such as the high-speed rail system in Taiwan (Kerh and Ting, 2005).

Several studies have applied IDW and Ordinary Kriging models to study PGA, such as the Seismic Hazard Microzonation of Ground Response Parameters in Bengkulu, Indonesia (Mase et al., 2020), Application of Ordinary Kriging Technique to Seismic Intensity Data in Italy (Rubeis et al., 2005), and Building Damage Hazard Zoning Using FKCN and IDW Algorithm in Banda Aceh, Indonesia (Faisal and Irwansyah, 2014). However, the spatial Regularized Spline model has never been used for PGA loading, which makes it a new method as compared with the IDW and Ordinary Kriging spatial models. Therefore, the purpose of this study was to compare the IDW, Ordinary Kriging, and Regularized Spline Spatial models in the PGA study to determine the best fit model for representing PGA map of West Java, Indonesia. West Java Province in Indonesia was selected as the study area due to its potential for vibrations generated through endogenous energy activity and history of earthquakes due to tectonics and volcanics activities. The findings of this research are expected to be useful for scientific studies related to the implementation of PGA.

2. Data and Method

2.1 Data

The data used in this study were hypocenter depths, earthquake magnitudes (minimum of 3.5 and maximum of 7), and earthquake epicenters which publicly available through https://earthquake.-usgs.gov/earthquakes/search/. The USGS showed 257 epicenters occurring in West Java Province during 38 years period (1982 to 2020) as ilustrates in Figure 1. The boundary of the study area, the West Java Province is also publicly available from https://tanahair.indonesia.go.id/portal-web/login, though registration is required before being able to download the data.

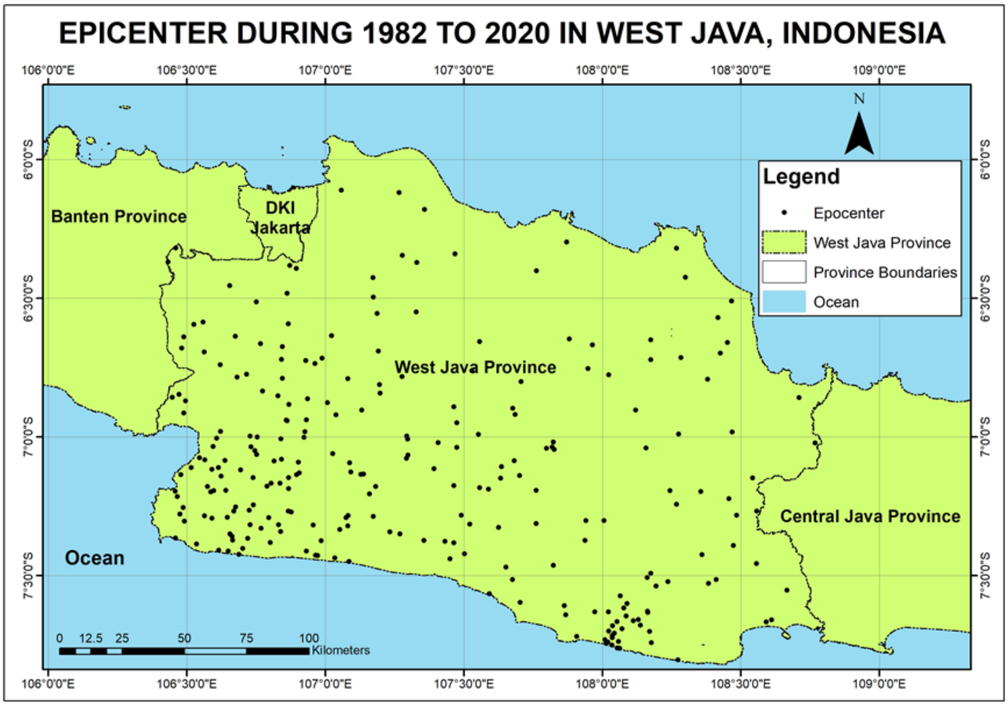

Figure 1: Study area

2.2 Peak Ground Acceleration (PGA) Calculation

The PGA was calculated based on the coordinate location data as well as the hypocenter depth and magnitude at each epicenter from the data obtained (see 2.1). PGA is determined based on Kanai (1196) empirical equation (1996) as follows:

$$PGA = b1\ [10^{(b2Ms-1.66+(3.6/R)logR-1.67+1.83/R)}]$$

Equation 1

Where:

PGA = Peak Ground Acceleration [gal]
b1 = 5/(T^0.5)
T = land dominant period
b2 = 0.61
Ms = surface wave magnitude
= -8.545 + 1.201 mb (Thenhaus et al, 1993)
Mb = body wave magnitude
= mb
= log10(A/T) + 0.01*D + 5.9 (Gutenberg and Richter (1956))
R = the hypocenter distance to the observer point [$R = [(x1-x2)^2+(y1-y2)^2+(z1-z2)^2]^{0.5}$]

The equation describes x1 latitude of calculation area, y1 longitude of calculation area, x2 latitude of epicenter earthquake and y2 longitude of earthquake epicenter.

2.3 Spatial Model

Three spatial models - the Inverse Distance Weighted (IDW), Ordinary Kriging, and Regularized Spline - were analyzed using ArcGIS 10.4 software with the algorithms available for each model. Each model has similar 257 coordinate points with reference to the results of the PGA calculation and the basic geostatistics was interpolated. However, each used different algorithms, according to what is provided in ArcGIS 10.4. Meanwhile, the complexity of the Ordinary Kriging model was adjusted by modifying the weight coefficient and variance of each core function (Li et al., 2020). Ordinary kriging empirical equation is as follow:

$$Z(s) = \mu + \varepsilon(s)$$

Equation 2

Where μ is an unknown constant:

$\varepsilon(s)$ = error value on Z(s)
Z(s) = the results of krigging

Regularized Spline empirical equation is as follow:

$$S(x,y) = T(x,y) + \sum_{j=I}^{N} \lambda_j R(r_j)$$

Equation 3

J = 1, 2, ..., N.
N = the number of points.
λ_j = coefficients found by the solution of a system of linear equations.
r_j = the distance from the point (x,y) to the j point.

T(x,y) and R(r) are defined differently, depending on the selected option.

The IDW model has the concept of literal spatial autocorrelation which means that the closer sample point to the estimated cell, the closer the cell value to the sample point value (Setianto and Triandin, 2013). IDW empirical equation is as follow:

$$z_0 = \frac{\sum_{i=1}^{s} z_i \frac{1}{d_i^k}}{\sum_{i=1}^{s} \frac{1}{d_i^k}}$$

Equation 4

Z_0 = Approximate value at point 0
Z_i = What is the value of z at the control point i
d_1 = Distance between point i and point 0
k = The larger k, the greater the effect of neighboring points
S = Number of points S used

The results of each value PGA point in pixel of IDW, Regularized Spline, and ordinary kriging were, therefore, extracted in the spatial model to ensure the value of each is based on the PGA point extraction.

2.4 Calculation of Root Mean Square Error (RMSE)

The accuracy of each model was analyzed using the Root Mean Square Error (RMSE) statistics which is usually applied for spatial and actual data. The model is believed to be more precise the closer the RMSE value to 0. This method has been adopted in several studies to measure the predicted and actual values (Wang and Lu, 2018).

$$\boldsymbol{RMSE = \pm\sqrt{\frac{1}{n}\sum_{i=1}^{n}[(x_i - y_i)^2]}}$$

Equation 5

Where:

RMSE = *Root mean square error,*
N = The number of point value
x_i = Pixel value at the referenced point i,
y_i = Pixel value at the point i
$\bar{x}$ = Pixel value at the referenced point i,
$\bar{y}$ = Pixel value at the point i

3. Results and Discussion

3.1 Peak Ground Acceleration (PGA)

The calculation of Peak Ground Acceleration (PGA) in West Java showed an average value of 27.001 gals as indicated in Figure 2. The highest value (74.563 gals) was observed in 2008 at the southern part of the province while the lowest one was 5.776 gals in 2018 at the Northwesternpart of the study area. Figure 2 shows that X and Y axis namely PGA and the number of PGA.

3.2 Spatial Modelling

Spatial modeling was conducted based on the PGA calculation (see equation 1). The comprehensive observation of the map analysis showed similar PGA spatial distribution patterns in the Inverse Distance Weighted and Ordinary Kriging models. On the other hand, the Regularized Spline showed very striking differences, particularly in the southern study area. The algorithm of each model, therefore, became a factor to determine the differences in the interpolated PGA values. Moreover, the Regularized Spline model is rarely used for spatial studies while IDW and Ordinary Kriging are often used. The northern area of the study was also observed to generally have low PGA values as indicated with the majority of green gradations in the spatial model presented in Figure 3.

Meanwhile, high PGA values are scattered in the southern and middle areas. Active volcanoes and faults observed in the central area of the province may be possible factors for vibrations while the coastal southern area is adjacent to the tectonic plates.

The analysis showed the PGA values mapped to the IDW model were ranged in 5.78 gal to 7.96 gal; Ordinary Kriging was ranged in 7.23 gal to 49.11 gal; and Regularized Spline was ranged between -96.512 gal to 137.42 gal. The IDW spatial model was discovered to have approximated the PGA calculation value of each epicenter; this means that this model may be the best spatial model amongst the three models analyzed. The Regularized Spline model has a negative value non-existent in the PGA calculation of each epicenter – which may be caused by converting point value data into a raster. Besides, Spline will always generate surface pass through every observed points; thus, the interpolated and obeserved values are always the same value. In summary, Spline interpolation is not frequently used because the prediction error cannot be assessed, and the prediction cannot be validated. The negative value is also most likely due to the ocean area in the southern part.

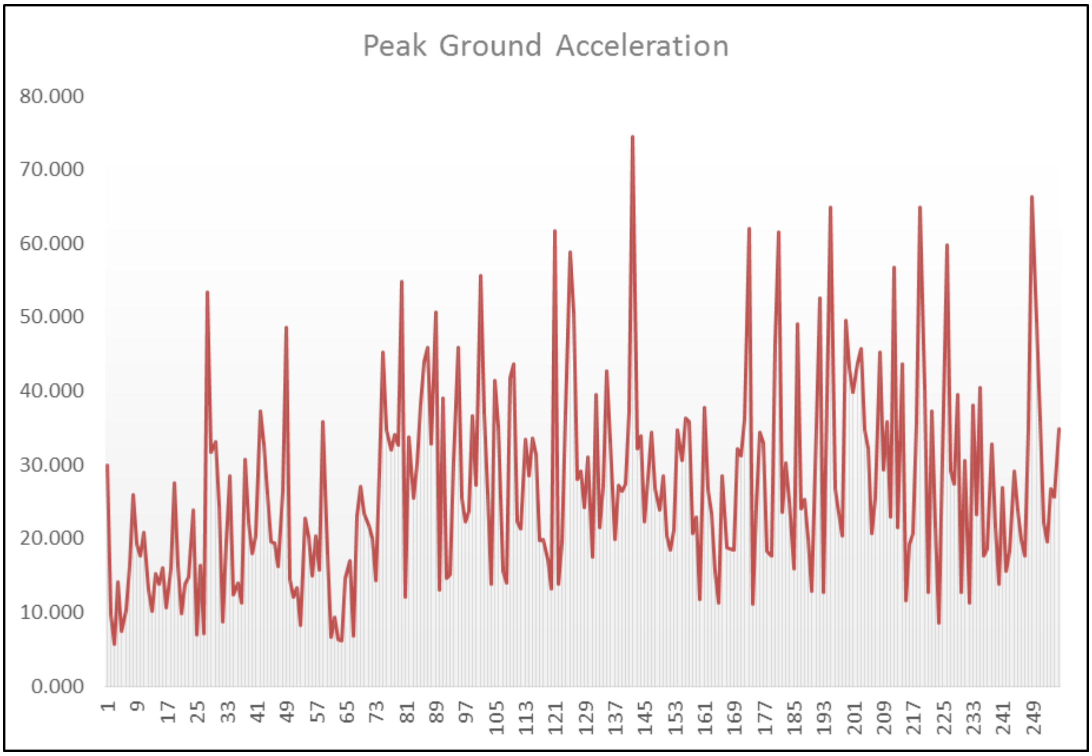

Figure 2: Peak ground acceleration results

3.3RMSE Calculation

RMSE was calculated to compare the calculated PGA values with calculations obtained from the IDW, Ordinary Kriging, and Regularized Spline models. The IDW model was observed to have the best RMSE value of 0.772352 when compared with the 7.169879 for Ordinary Kriging and 1.140802 for Regularized Spline (see Table 1).

Table 1: Root Mean Square Error Results

Method	**RMSE**	**Max**	**Min**	**Average**
IDW	0.772352	71.975	5.783	26.998
Regularized Spline	1.140802	69.827	5.734	26.933
Ordinary Kriging	7.169879	48.984	7.556	27.376
PGA		74.563	5.776	27.001

The infographic comparison with the min-max values among each spatial model and the PGA calculation results also showed that IDW has the closest min-max values with the PGA. In addition, the Spline's RMSE results is the second closer to PGA RMSE result although the Regularized Spline's overall raster value is very different from the PGA calculation. This was assumed to be due to the value mismatch outside the study area or the existence of negative value in the green part of the ocean as shown in Figure 3.

4. Conclusion

The calculated Peak Ground Acceleration (PGA) value showed that West Java has an average value of 27.001 gal during 38 years period. The highest recorded value was 74.6 gal in 2008 while the lowest was 5.776 gal in 2018. The analysis also showed the interpolated PGA values using IDW model (min 5.78 gal and max 71.96 gal) to be the closest to the calculated PGA values (min 5.78 gal and max 74.56 gal).

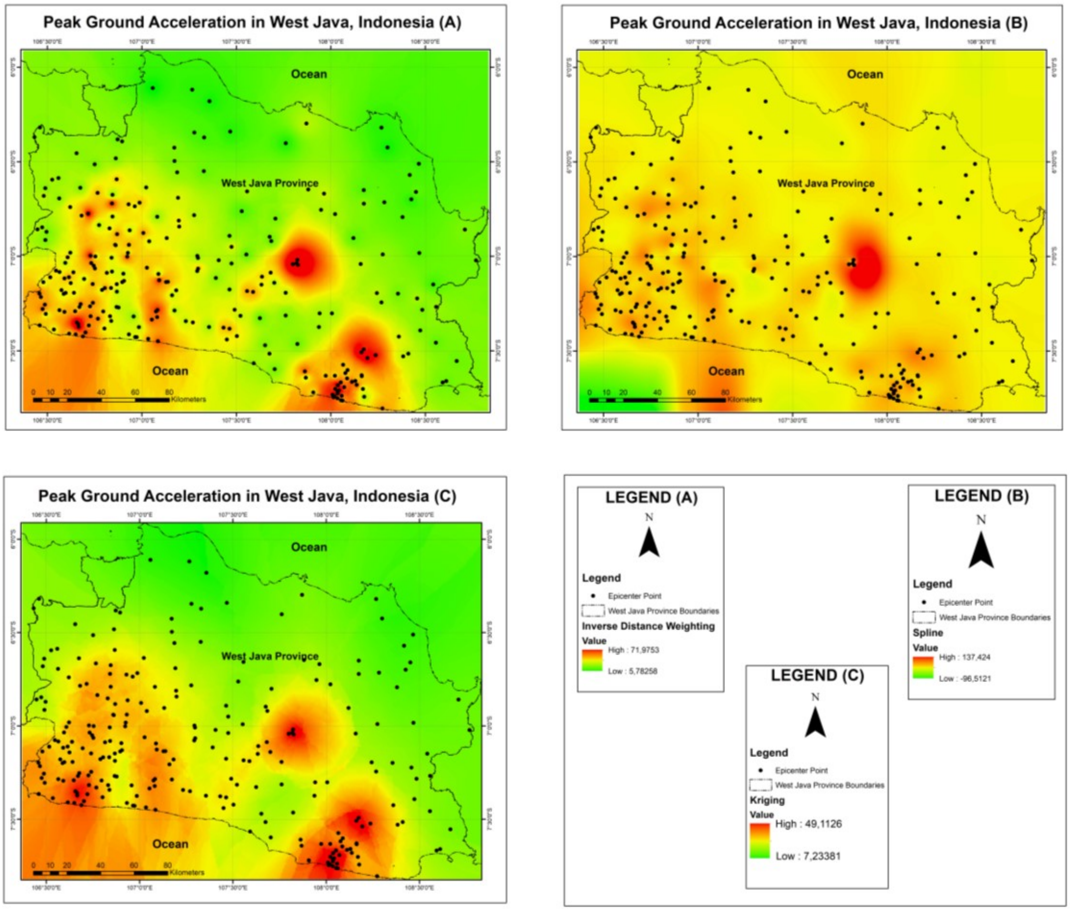

Figure 3: Peak Ground Acceleration in West Java, Indonesia (A) IDW (B) Spline and (C) Kriging

Ordinary Kriging had 7.23 gal 49.11 gal, while Regularized Spline had -96.5121 gal to 137.42 gal. The different minimum and maximum values among each model were believed to be caused by the algorithms variations in each spatial modeling process. Moreover, the infographics and proximity of the maximum and minimum values showed that IDW is a model with values closer to the PGA factual results. The IDW's RMSE result also showed values the closest to 0 (0.772352) among the three models (Ordinary Kriging 7.169879 and Regularized Spline 1.140802, respectively). This means that IDW is the most suitable among the three for the spatial modeling of PGA studies in West Java Province.

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