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Using Geostatistics for Spatial Analysis of Soil Moisture Content, Electrical Conductivity, and pH at Paddy Fields

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ABSTRACT

Soil is dynamic due to various internal and external processes exerted on the soil, resulting in unique soil characteristics in space in short and long distances. Geostatistics (kriging) is the method of quantifying the spatial variation of soil properties. This research was mainly aimed at applying geostatistics to quantify and interpolate the spatial dependence and structure of three soil properties, namely pH, EC, and Soil Moisture Content (SMC) in a small area. This research was conducted on paddy fields in Mlandingan Kulon Village, Situbondo Regency. Sampling was conducted on an area of 9.2 ha with 31 sample points. Normal data distribution was found for pH and EC, whereas this was not the case for SMC. The results of the analysis showed that most of the pH values were alkaline (>8), EC values were non-saline (<2 mm/cm), and SMC was in the low category (<20%). The results show that for three soil properties, weak dependencies were observed. The values of Root Mean Square Error (RMSE) confirmed that kriging with exponential was better compared to the spherical model, resulting in the RMSE of 0.546 (pH), 0.041 (EC), and 1.512 (SMC).

Keywords: EC, geostatistic, pH, SMC, spatial analysis

INTRODUCTION

Soil is dynamic due to various internal and external processes exerted on the soil. Because of this, the soil may portray significantly different characteristics within space due to the difference in the intensity of processes. Soil-forming factors may affect the internal process of soils, while external factors could alter or enhance the soil-forming processes, resulting in different soil properties (Phillips, 2017). Particular soil properties may provide variation within a short distance, while others may exhibit variation over long distances (Khan et al., 2021; John. 2021; Cahyana et al., 2022). Information on this variation benefits soil management (Wicaksono et al., 2019). From the above, it is clear that previous studies have long recognized the importance of soil variation in space. This recognition of soil variation has led to the development of methods for quantifying the variability of soil properties.

The methods for quantifying the spatial variation of soil properties have been established (Rogowski, 1996; Chen et al., 2021; Bangroo et al., 2021; Zhang and Hartemink, 2021). Geostatistics is the most notable one, and kriging (one of the geostatistical methods) have been used extensively for enumerating spatial variability of soil properties (AbdelRahman et al., 2020; Shahinzadeh et al., 2022). Geostatistics is mainly utilized to produce maps and thus provide estimates of the values of soil properties for unsampled sites (Bautista, 2021). The use of geostatistics leads to the making of maps cheaper and faster maps (Bilonick, 1991; Goovert, 2001)

The merit of kriging for quantifying variability of soil properties has long been acknowledged for quite a long time, and the applications for agriculture have also been prominent. Shit et al. (2016) employed geostatistics for counting spatial variability of pH, electric conductivity (EC), phosphorus (P), potassium (K), and organic carbon (OC) and found that Ordinary Kriging interpolation can expose clearly the spatial distribution of soil properties and also reveal that the sufficiency of the distance of the samples in their study. Therefore, it is interesting

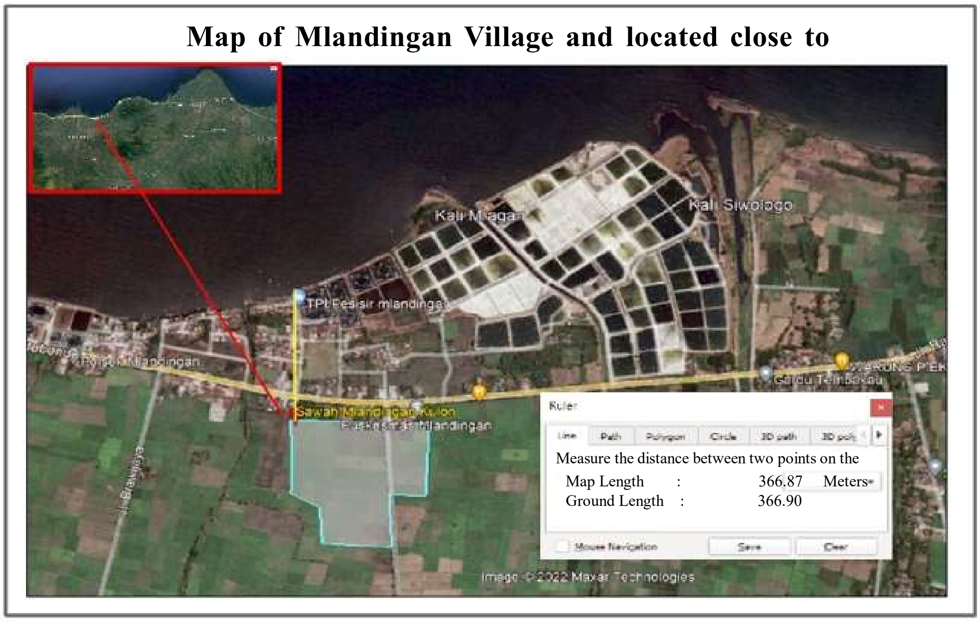

Figure 1. Map of Mlandingan Kulon Village and the distance to the beach.

to study the application of kriging for studying the spatial variation of soil properties based on this condition. This research was mainly aimed at applying geostatistics to quantify and interpolate the spatial dependence and structure of three soil properties, namely pH, EC, and soil moisture content in the study area.

MATERIALS AND METHODS

The research was conducted in the paddy fields of Mlandingan Kulon Village, Situbondo Regency. Geographically, Mlandingan Village is located at coordinates 805010.888 (Easting) and 9143313.20 (Northing) and 805307.884 (Easting) and 9143368 (Northing) with the datum WGS 1984 UTM, Zone 49S. The study area was 9.2 ha, with the number of soil samples for this study being thirty-one. Sampling was carried out using the grid sampling method. According to Wollenhut and Wolkwski (1984), this method is relatively easy to do in flat paddy fields because of the determination of the same distance in forming a grid. Sampling was conducted at a distance of 55 m × 55 m with a 0-20 cm depth below

Figure 2. Map of sample point location.

the ground surface. The map of soil sample location can be seen in Figures 1 and 2. Soil sample analysis was conducted for three soil properties: pH, EC, and soil SMC. The analysis was carried out in the laboratory using absolute moisture content and electrical conductivity methods to determine the SMC and EC values.

In contrast, a pH meter was used to determine pH. The laboratory analysis results were then analyzed by ordinary kriging interpolation using spherical and exponential semivariogram models. According to (Respatti et al., 2014), quoted in Isac and Srivastava (1989), ordinary kriging is also known as linear kriging because, in the process, it uses a weighted linear combination of known sample data to make predictions or estimates. Ordinary kriging was chosen because it does not contain outlier data or data that is very different from other data (Rozalia et al., 2016). The following is an ordinary kriging formula, according to (Rozalia et al., 2016):

$$\hat{z}(s) = \sum_{i=1}^{n} wi\ Z(si)$$

$\hat{z}(s)$: estimated value at an unsampled location
Wi : weight coefficient of $\hat{z}(s)$, with $\sum_{i=1}^{n} wi = 1$
Z(Si): value at sampled location
N : samples

Table 1. The results of laboratory analysis of three soil properties in the study area.

Sample	Easting	Northing	SMC		EC		pH	Criteria
			(%)	Criteria	(mm cm^{-1})	Criteria		
1	805034.4137	9143350.315	9.1	Low	0.213	Non-saline	8	Slightly alkaline
2	805034.4137	9143300.315	12.5	Low	0.215	Non-saline	7.08	Slightly alkaline
3	805034.4137	9143250.315	13.4	Low	0.225	Non-saline	7.86	Slightly alkaline
4	805034.4137	9143200.315	12.7	Low	0.186	Non-saline	9.96	Alkaline
5	805084.4137	9143350.315	12	Low	0.187	Non-saline	7.68	Slightly alkaline
6	805084.4137	9143300.315	13.3	Low	0.229	Non-saline	7.8	Slightly alkaline
7	805084.4137	9143250.315	12.2	Low	0.196	Non-saline	7.8	Slightly alkaline
8	805084.4137	9143200.315	12.5	Low	0.178	Non-saline	7.27	Neutral
9	805084.4137	9143150.315	10.7	Low	0.205	Non-saline	8.04	Slightly alkaline
10	805084.4137	9143100.315	12	Low	0.264	Non-saline	7.82	Slightly alkaline
11	805134.4137	9143350.315	11.2	Low	0.225	Non-saline	7.97	Slightly alkaline
12	805134.4137	9143300.315	12.8	Low	0.268	Non-saline	7.89	Slightly alkaline
13	805134.4137	9143250.315	10.6	Low	0.185	Non-saline	7.09	Neutral
14	805134.4137	9143200.315	13.3	Low	0.186	Non-saline	8.11	Slightly alkaline
15	805134.4137	9143150.315	11.2	Low	0.181	Non-saline	7.6	Slightly alkaline
16	805134.4137	9143100.315	12.9	Low	0.176	Non-saline	7.69	Slightly alkaline
17	805184.4137	9143350.315	12.3	Low	0.234	Non-saline	7.7	Slightly alkaline
18	805184.4137	9143300.315	10.7	Low	0.258	Non-saline	7.69	Slightly alkaline
19	805184.4137	9143250.315	13.1	Low	0.218	Non-saline	7.92	Slightly alkaline
20	805184.4137	9143200.315	12.3	Low	0.237	Non-saline	8.02	Slightly alkaline
21	805184.4137	9143150.315	11.9	Low	0.204	Non-saline	8.05	Slightly alkaline
22	805184.4137	9143100.315	12.3	Low	0.17	Non-saline	8.14	Slightly alkaline
23	805234.4137	9143350.315	11.9	Low	0.2	Non-saline	7.9	Slightly alkaline
24	805234.4137	9143300.315	9.5	Low	0.16	Non-saline	8.04	Slightly alkaline
25	805234.4137	9143250.315	8.2	Low	0.164	Non-saline	8.1	Slightly alkaline
26	805234.4137	9143200.315	8	Low	0.145	Non-saline	7.77	Slightly alkaline
27	805234.4137	9143150.315	8.7	Low	0.2	Non-saline	7.87	Slightly alkaline
28	805234.4137	9143100.315	10	Low	0.291	Non-saline	7.55	Neutral
29	805284.4137	9143350.315	13.2	Low	0.193	Non-saline	8.12	Slightly alkaline
30	805284.4137	9143300.315	12.4	Low	0.18	Non-saline	8.02	Slightly alkaline
31	805284.4137	9143250.315	11.9	Low	0.22	Non-saline	8.05	Slightly alkaline

Kriging interpolation uses a variogram to measure spatial correlations for each observation (Respatti et al., 2014). Using a semivariogram, three parameters determined are sill, range, and nugget. By analyzing these three parameters, spatial dependency can be determined. A complete overview on the uses of kriging can be found in Johnston et al., (2021). The next step was conducting kriging interpolation, resulting in krigged maps for three soil properties: EC, SMC, and pH. The materials and tools used in this research are topographic maps at 1:25.000, aquades, soil samples, pH meter, EC meter, analytical balance, desiccator, oven, ArcGIS software, UTM Geo Map software, and SAS Planet software.

RESULTS AND DISCUSSION

Table 1 shows the laboratory analysis results of three soil properties: EC, SMC, and pH; the three soil properties vary in the study area. There does exist spatial variation of the values of three soil properties in every sample location by considering the values of standard deviation, namely 0.03 (EC), 1.54 (SMC), and 0.4732(pH), as shown in Table 2. This variation is expected to occur in the study area due to the variation of soil-forming factors and mainly human-induced activities. This variation is interesting for this study regarding spatial dependence and structure because the study area is considered negligible (about 9.2 ha). The following will discuss these three soil properties' spatial dependence and structure.

Trend Analysis of Electrical Conductivity, Soil Moisture Content (SMC) and pH

Figures 3, 4, and 5 show the trend analysis results. Based on the graph, there are different trend patterns in EC, SMC, and pH. The trends are as follow: (a) EC has a trend of gradually increasing from east to west (red line from left to right in Figure 3) and gradually decreasing and then increasing from north to south (blue line in Figure 3); (b) SMC has a trend of being slightly increasing from east to west (red line in Figure 4) and slightly decreases from north to south blue line in Figure 4); (c) pH has different pattern, it seems that there is gradual decrease then followed by a gradual increase from east to west (red line in Figure 5), whereas there is no difference of trend from north to south (blue line from left to right in Figure 5). As shown in Figures 3, 4, and 5, three soil properties show different patterns of trends.

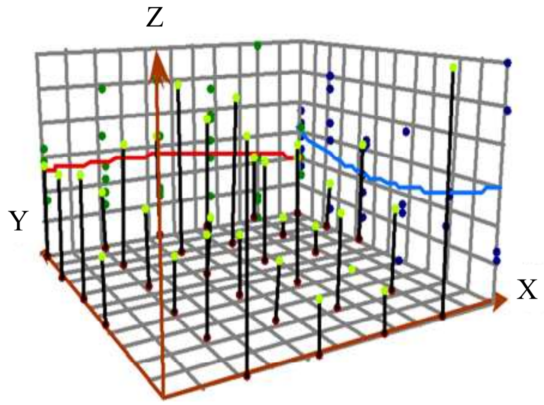

Figure 3. Trend Analysis of EC.

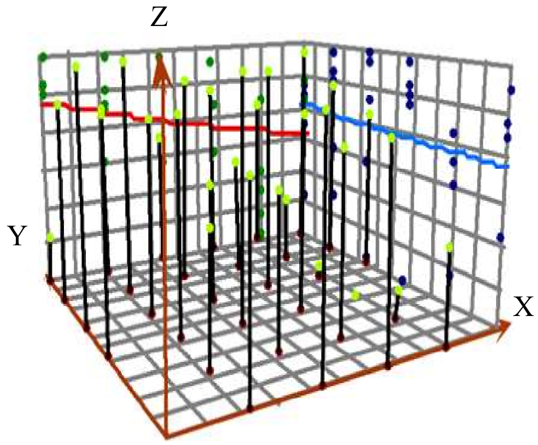

Figure 4. Trend Analysis of SMC.

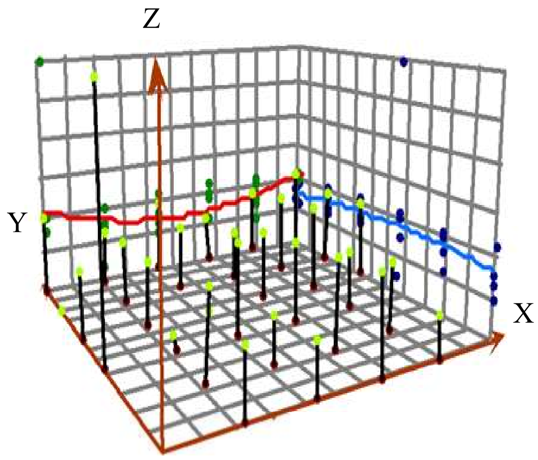

Figure 5. Trend Analysis of pH.

Fundamental Statistical Analysis of EC, SMC, and pH

Table 2 is the evidence of the above description; there is a similarity in the values of EC for the whole

Table 2. Histogram Analysis of EC. SMC. and pH.

Variable	Result					
	Number of data	Min	Max	Mean	median	std. dev
EC	31	0.145	0.291	0.206	0.2	0.0338
SMC	31	8	13.4	11.574	12	1.5483
pH	31	7.08	9.96	7.89	7.89	0.4732

Table 3. Semivariogram analysis of EC, SMC, and pH.

Variable	Nugget Effect	Major Range	Minor Range	Direction	Partial Sill	Sill	Lag Size	Nugget/Sill x 100%	Model
pH	0.00212	480	160.55	11.25	0.00079	0.0029	40	72.82	Exponential
SMC	0.00870	283.827	94.93	169.62	0.00748	0.0161	40	53.78	Exponential
EC	0.02130	480	160.55	60.99	0.00245	0.0237	40	89.65	Exponential

study area. Slightly variation was observed on the pH, whereas more significant variation was observed for SMC. Considering the mean and median values, the data provides normal distribution, except for soil moisture content. Besides, the standard deviation at pH and EC is close to zero and more negligible than SMC. The pH and EC values have more uniform values than SMC values.

Semivariogram Analysis of Soil Properties

The following table (Table 3) shows the results of the semivariogram analysis. The nugget effect for EC was the highest, whereas a minor nugget effect occurred in SMC, and the lowest was pH. According to (Krisdianto et al., 2018), the variation of interpolated data values will increase the nugget effect**.** Within the small distance, a variation occurred, which may relate to the slight variation due to natural or human-induced processes. The human-induced process (farming practices conducted by farmers) is the most likely to affect this.

There is a pattern of anisotropy for three soil properties. As seen in Table 3 and Figures 6, 7, and 8, the direction of anisotropy was 11.25° 169.62°, and 90.99° for pH, SMC, and EC, respectively. The primary and minor ranges values were also different for these three soil properties, with the highest range observed in pH and EC, indicating that the spatial dependence occurred at about 480m (major ranges) and 160.55m (minor ranges). Therefore, these two

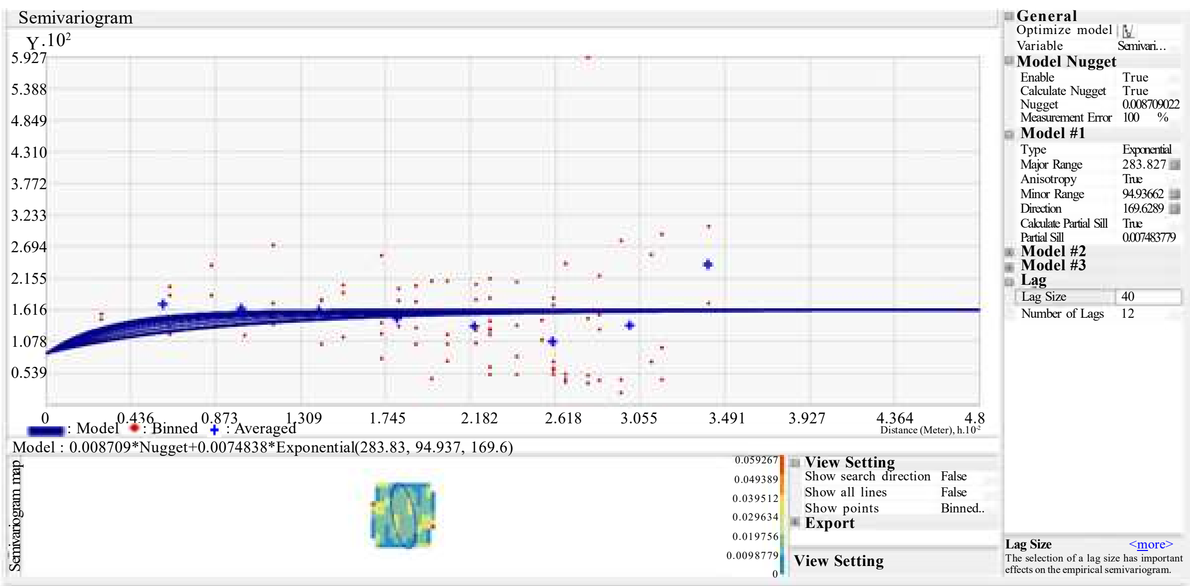

Figure 6. Semivariogram of SMC.

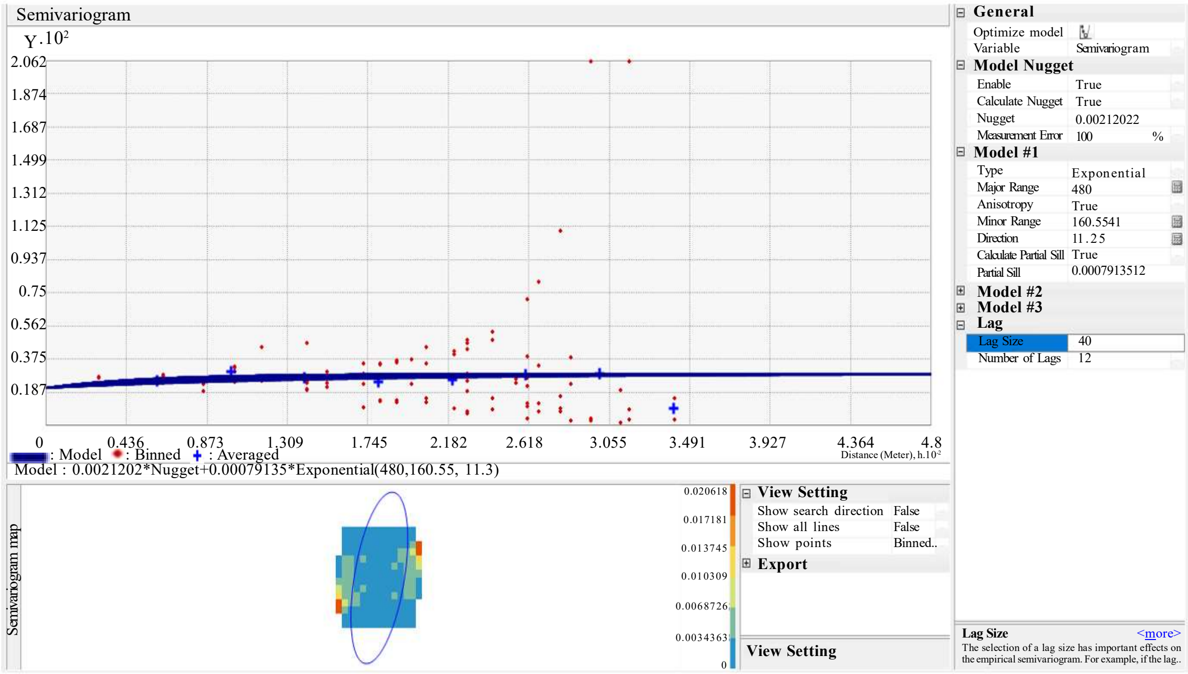

Figure 7. Semivariogram of pH.

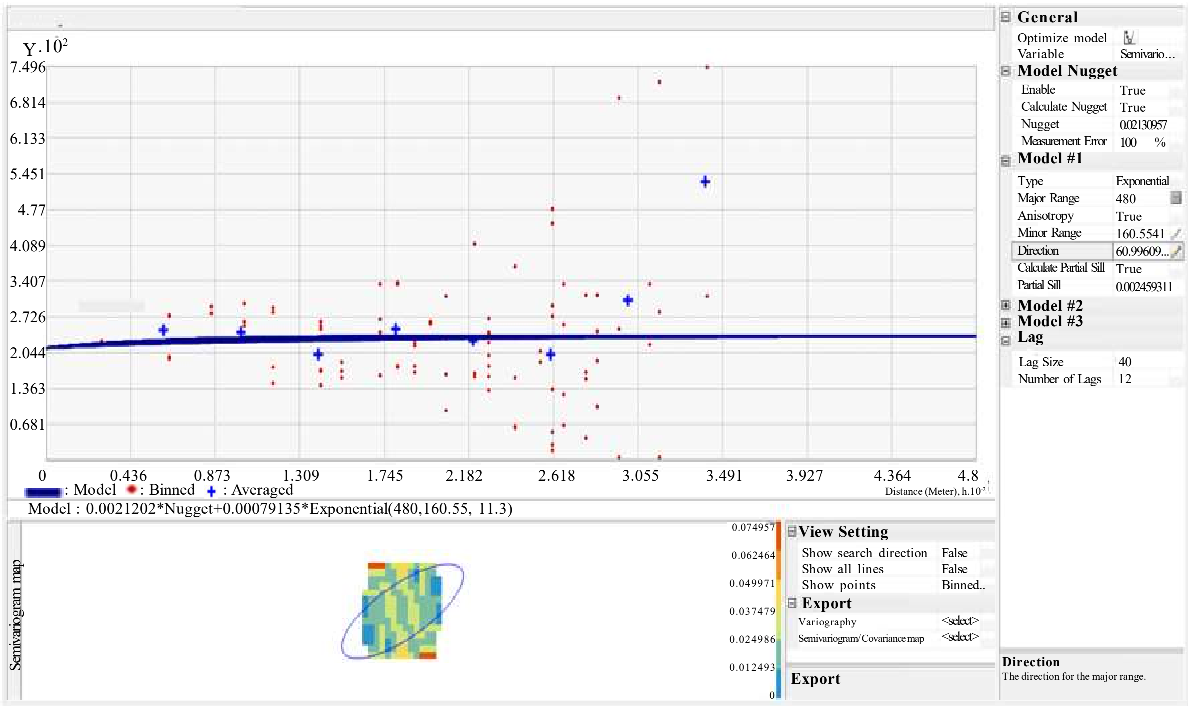

Figure 8. Semivariogram of EC.

soil properties exhibit a similar structure. No more spatial relationship exists beyond this distance (Oliver and Webster (2015).

A small range was observed for SMC, the observed ranges were 283.83 (major) and 94.93(minor) (Table 3 and Figure 6). Compared to the other two soil properties, a smaller range value was observed for EC, meaning that a shorter distance of spatial dependence was observed for SMC. Finally, the strength of the spatial relationship can be seen from the value of the nugget/sill, with values of 72.82 (pH), 53.78 (SMC), and 89.65 (EC), respectively. Even though there is spatial dependence, however, the small distance variation of these soil properties was also prominent. In other words, the nugget effect is also considered high.

Krigged Map of Soil EC

Figure 9 shows the interpolated values of soil EC. The values of EC were mainly categorized as medium (minimum = 0.181 mm cm^{-1} and maximum 0.218 mm cm^{-1}), indicating a non-saline condition. The soil in the study area has low salt content, and this is not a prohibitive factor for growing paddy. As illustrated in the map, the range of EC values from 0.145 mm cm^{-1} to 0.181 mm cm^{-1} has an area of 0.16 ha. The range of EC values from 0.181 mm cm-1 to 0.218 mm cm-1 occupies an area of about 8.03 ha. Subsequently, the ranges of EC values ranged between 0.218 mm cm^{-1} to 0.291 mm cm^{-1} having an area of 1.06 ha. The interpolated EC map is considered sufficiently accurate by using ordinary kriging. This result agree with Sahbeni and Székely (2022) stating that kriging with varied method can be used to accurately provide spatial variability of EC.

Krigged Map of Soil Moisture Content

Figure 10 shows the krigged map of SMC in the study area. The minimum and maximum values of soil moisture content in the study area are 8% and

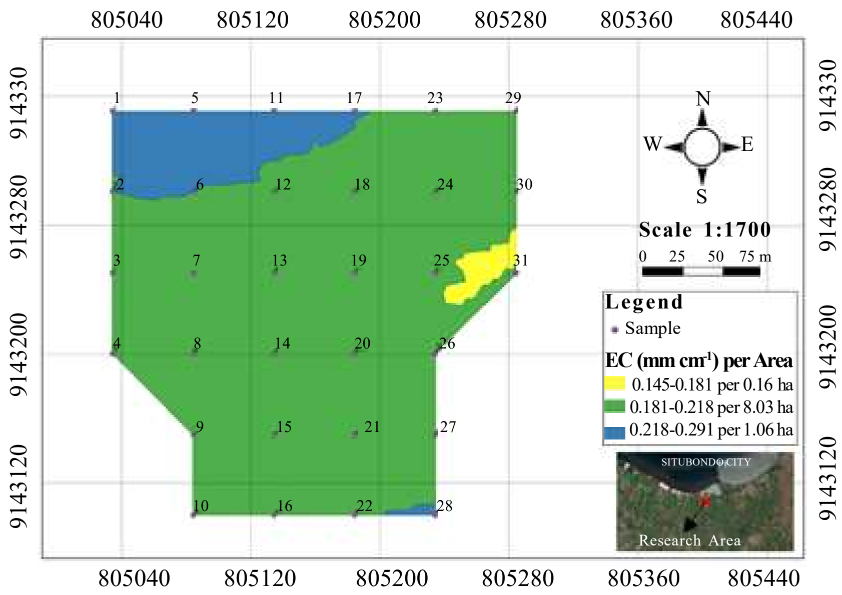

Figure 9. Map of EC.

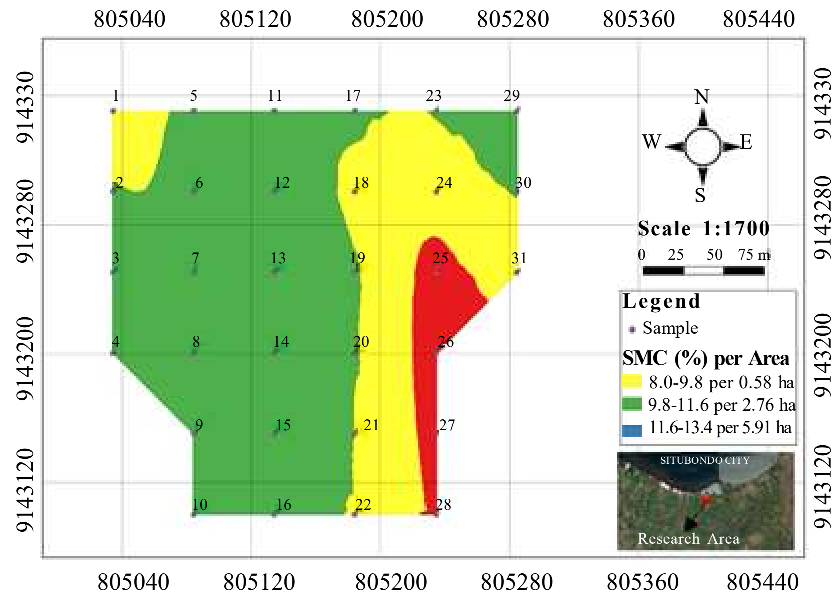

Figure 10. Map of SMC.

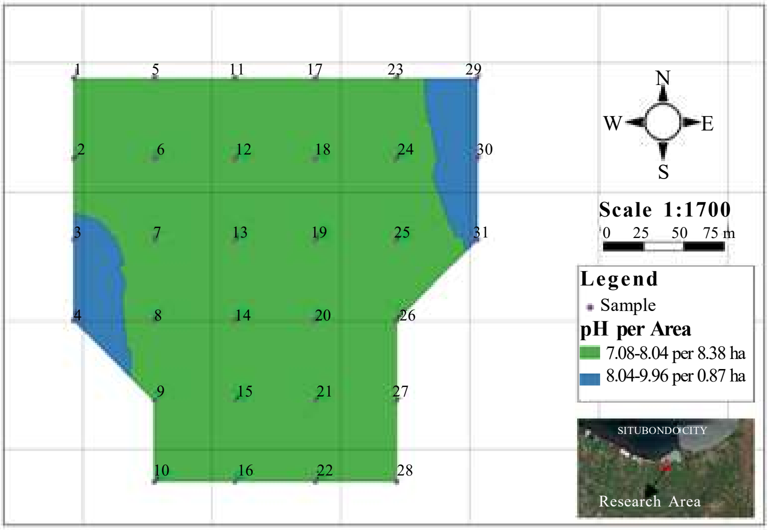

Figure 11. Map of pH.

13.4%, respectively (Table 1). This range of values is classified as low by referring to the standard. According to Syuaib and Astika (2015), a water content value of less than 20% is included in the low category. There are two possible reasons for this (1) the study area is quite close to the beach and has a sandy texture, with the consequence that the ability to store the water is low; (2) The study area has quite dry climate/ Type E according to the classification of Schmidt and Ferguson. The classified map of soil moisture content shows that the values between 8.0% and 9.8% have an area of 0.58 ha, and the values from 9.8 to 11.6% show an area of 2.906 ha. Then, the values from 11.6 to 13.4% occupy the area of 5.91 ha.

Krigged Map of soil pH

The fact that soil pH is the key for soil nutrient availability, the analysis of pH spatial variability is an important for soil management (Zandi et al., 2011). Figure 11 shows the krigged map of soil pH in the study area. The minimum and the maximum value of soil pH in the study area are 7.08 and 9.96. This range of value is classified as high (alkaline). There is a possible reason for this the study area is close to the coastal area. The distance between the rice fields and the coast is about 380 m. According to (Zewd and Siban, 2021), areas close to the coast have an alkaline soil pH due to dissolved sodium carbonate. The classified map of soil pH shows that the value 7.08 and 8.04 has an area of 8.38 ha, and the pH values between 8.04 and 9.96 have an area of 0.87 ha.

Alkaline soil conditions certainly affect rice plants. Ray et al., (2014) state that alkaline pH conditions will cause low soil infiltration, a difficulty for plants to absorb nutrients, cause corrosiveness to plant roots and stems, and possibly interfere with plant metabolism. Alkaline soil will increase the Cu and Mn content in the soil which is a cause of plant poisoning (Ray et al., 2014).

The above discussion shows that soil EC, SMC, and soil pH are three essential components that could impede the growth and development of rice in the study area. While SMC is probably the most effortless to solve, EC and pH may provide significant challenges to manage since these two properties are more affected by natural soil-forming processes. Significant endeavors must be conducted to minimize the effects of EC and pH on rice production.

Efforts to overcome the problem of low SMC and high pH values in the rice fields of Mlandingan Kulon Village, Situbondo Regency, need to be pursued. The paddy field soil can be improved on the soil properties of pH and SMC. Improvement

Table 4. Analysis RMSE of EC, SMC, and pH.

Variable	RMSE	
	Semivariogram Shperical	Semivariogram Eksponential
EC	0.04078	0.04072
SMC	1.5282	1.5116
pH	0.54713	0.54595

of SMC can be carried out by adding organic matter. According to (Roidah, 2013), organic matter can improve soil physical properties such as porosity, soil structure, and water storage capacity and helps exchange cations in the soil. Adding organic as much as 50 g 5 kg^{-1} of soil or 20 Mg ha^{-1} provided the best results in binding water to clay and clay (Intara et al., 2011).

The pH condition can be improved by adding a mixture of biochar with manure and sulfur. Adding a mixture of biochar with manure and a mixture of biochar with sulfur may reduce the pH values suitable for optimum production of rice yields (Salem et al. 2019). A mixture of biochar with manure and sulfur at a dose of 1:1 during composting in 3 months can reduce pH (Salem et al., 2019). Legume plants are also used in lowering pH because, in N fixation, the acid capacity in the root rhizosphere will also increase so that the pH of alkaline soil will decrease (Tavakkoli et al., 2022).

Root Mean Square Error of interpolated Soil Properties

Table 4 shows the values of RMSE of soil properties, the different values of RMSE were found for different semivariogram models. The results show that the values of RMSE for SMC were higher for spherical and exponential semivariogram models. They indicate that Kriging interpolation may be more appropriate for studying the smooth variation of phenomena (EC and pH) and may not be for the data having high variances (EC). From this table, it is also clear that EC was more accurately mapped by kriging interpolation than pH and SMC.

CONCLUSIONS

The pH obtained was predominantly in the alkaline category (pH > 8), the SMC was in the low category (<20%), and the EC was in the non-saline category (<2 mm/cm). Although spatial dependency of soil properties occurs in the study area, the nugget sill ratio shows that the dependency is considered weak. Variability in smaller distances than in soil samples is likely responsible for this. The implication for using kriging in small areas is that the distance of samples must be determined very carefully to obtain appropriate variability.

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