GIS-BASED APPROACH TO IDENTIFY THE SUITABLE LOCATIONS FOR SOIL SAMPLING IN SINGAPORE

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ABSTRACT:

Shallow slope failures due to rainfall commonly occur in residual soil, especially in tropical areas like Singapore. Therefore, it is critical to understand the distribution of residual soil properties throughout Singapore Island. Proper procedures are required for selection of appropriate locations of soil sampling to obtain the representative soil properties. The aim of this study is to establish the necessary procedures and methods which are applicable to select suitable locations for soil sampling in Singapore. In this study, the Geographical Information System (GIS) with the incorporation of three layers: digital elevation model (DEM), slope angle, and the soil sampling locations from past studies were used to generate suitability map for determination of soil sampling locations in Singapore. Five suitability classes were implemented in each layer: very low, low, medium, high, and very high. Four types of spatial analyses such as "Analysis by weights", "Inference matrix method", "Fuzzy Overlay Gamma method", and "per-cell statistic maximum method (PCSM)" were assessed to identify the appropriate method for determination of the suitable locations for soil sampling in Singapore. These analyses were carried out using Spatial Analyst Tools in ArcGIS environment. The results of this study indicated that the spatial analysis by weights and Fuzzy Overlay Gamma are suitable for determination of soil sampling locations up to 100 data points. The spatial analysis using the inference matrix is suitable for determination of limited number of soil sampling locations. The spatial analysis using the PCSM method is suitable for determination of large number of soil sampling locations. The findings from this study will benefit the practical engineers in surveying as well as other related researchers for determination of suitable locations of soil sampling.

Key-words: Spatial Analyst Tools, suitability map, soil sampling, digital elevation model, soil investigation.[1]

1. INTRODUCTION

The earth's atmosphere is naturally composed of a number of gases that act like the glass panes of a greenhouse which are able to retain heat to keep the temperature of the Earth stable at an average temperature of 16 ºC. The average surface temperature of the earth would be around -10 ºC without the natural warming effect of these gases, carbon dioxide (CO2) (the most prolific among other gases), methane (CH_4), nitrous oxide (NO_2),

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ozone (0_3) and halocarbons. However, study by IPCC (2013) indicated the increase in the concentrations of these gases in the atmosphere which was resulted in the de-stabilizing effect on the global climate. This phenomenon, referred to as global warming is a major issue all around the world with its negatives effects on the climate, ecosystems, water resources, and human activities (Haeberli et al., 1999; Kargel et al., 2005; Oerlemans, 2005; Nistor & Petcu, 2015; Păcurar, 2015; Collins, 2008; Rahardjo et al., 2016).

Climate changes may cause extreme weather events in the world, such as the alteration in the rainfall pattern, amount, intensity and frequency. Previous studies indicated that rainfall events have become more intense in a number of countries (Fujibe, 2008; Groisman et al., 2005; Kuhn et al., 2011; Kristo et al., 2017). The increase in rainfall intensity may increase the impact of natural hazards, namely flooding and slope failures. Prolonged and heavy rainfalls in tropical countries have been observed in recent years. The report from IPCC (IPCC 2013) showed that it is expected that rainfall intensity in South East Asia, including Singapore will increase about 2 to 15 %, according to A1B scenario of the forth assessment report (AR4). The increase in rainfall intensity creates a risk that affects the environment sustainability. In this region, numerous slope failures commonly occur in steep residual soil slopes with a deep groundwater table during rainfalls (Toll et al., 1999; Rahardjo et al., 2013; Singh et al., 2008; Tohari, 2012; Jotisankasa et al., 2010).

Residual soil slopes have heterogeneous characteristics. Due to weathering, the soil properties of residual soil vary with depths for different locations in Singapore (Rahardjo et al., 2004). Permeability and shear strength vary gradually with depth, controlling both local seepage response to rainfall infiltration and location of the shear surface (Rahardjo et al., 2012). The variability of residual soil properties must be taken into account in the seepage and stability analyses of slopes. In this case, the proper number of soil sampling is necessary in the development of spatial distribution of soil properties with high accuracy. However, a large number of soil sampling contributes to the high cost of soil analyses. Therefore, it is necessary to have an appropriate tool for spatial analyses of saturated and unsaturated soil properties.

GIS applications are commonly used for spatial analyses in the engineering and environmental fields. Special function in ArcGIS environment called Spatial Analyst Tools were used by many researchers for determination of suitable locations of data collection in the development of high accuracy spatial distribution of those particular data (McCoy & Johnston, 2002). Dezsi et al. (2015) used GIS approach to select the suitable locations for a winter resort in the Western Carpathians. Several researchers used Spatial Analyst Tools in ArcGIS for determination of the spatial distribution of groundwater and climatic data in different regions of South Europe (Baltas, 2007; Nistor et al., 2015; Nistor, 2016). Paul et al (2002) and Elshehaby & Taha (2009) adopted the GIS techniques for the mapping of the spatial distribution of glaciers and measurements of the environmental changes (i.e. hydrogeology, climate, glaciology) in Switzerland. Limited research works were performed using GIS technique for landslides investigations and slope hazard risk development (Dai & Lee, 2002).

Sambah & Miura (2014) determined the vulnerable areas to tsunami in the eastern coast of Japan using Spatial Analyst Tools based on pair-wise comparison matrix in GIS. Șerban et al. (2016) used unmanned aerial vehicle (UAV) technology and GIS to delineate the flood-prone area in the North-East of Apuseni Mountains, Transylvania. The remote sensing and the Spatial Analyst Tools in ArcGIS were used to determine the multi criteria evaluation for development of landslide susceptibility map in the Haraz Watershed, Iran (Pourghasemi et al., 2012).

The soil quality and variability of salinity at spatial scale in Dawling National Park from southwestern Mauritania was checked and analayzed using GIS by Abidine et al. (2018). Cervi et al. (2010) used the statistical and deterministic methods for the development of landslides susceptibility map in the Northern Apennines, Italy. Bouajaj et al. (2016) utilized GIS applications for slope stability analysis in the development of slope susceptibility map. Based on the GIS, Murekatete & Shirabe (2018) applied spatial and statistical analyses to determine the variability of least-cost paths using raster artificial landscape data. In the city of Palermo, Dardanelli et al. (2017) determined the acoustic map of the vehicular traffic of an urban agglomeration using GIS technology. In their study, the cartography analysis including the terrain morphology, traffic flow integration, and resident population in the area were the main data used for the acoustic map for vehicular traffic. Bilaşco et al. (2018) used GIS technology to determine the accessibility of agricultural lands in the territory of Teiuş, Alba-Iulia, and Sebeş.

The objective of this study is to investigate an appropriate method for the development of the suitability map for soil sampling locations in Singapore. The scope of works include spatial analyses using Spatial Analyst Tools based on four methods in ArcGIS environment.

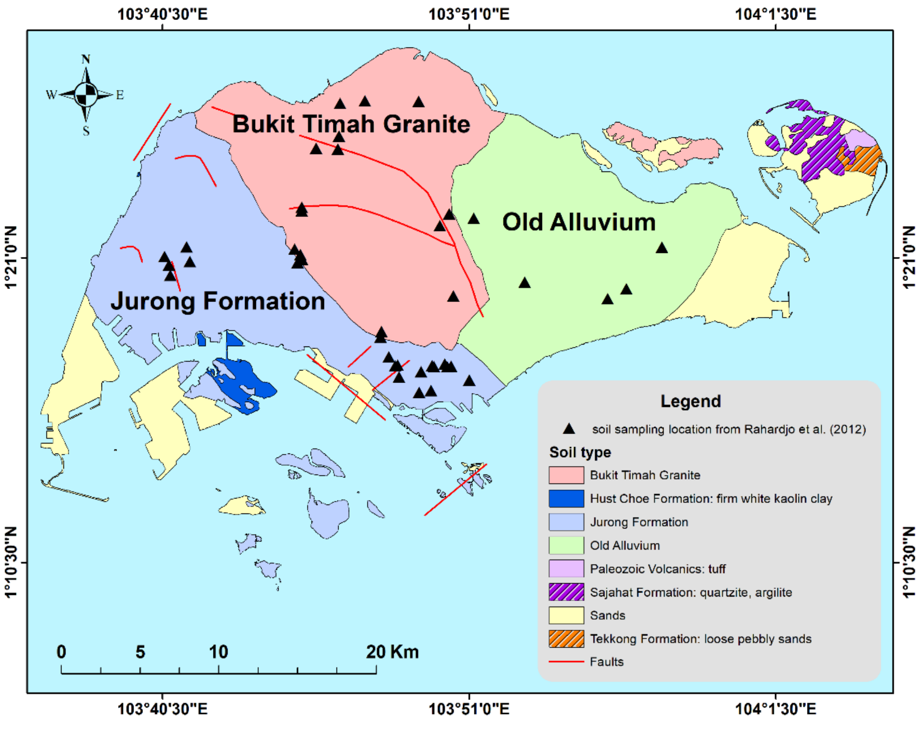

Fig. 1. Main soil formation in Singapore and the location of the soil sampling from Rahardjo et al. (2012). Background image source: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

2. MATERIALS AND METHODS

2.1. Residual soils in Singapore

Residual soil is the product of the in-situ mechanical and chemical weathering of underlying rocks, which have lost their original rock fabrics. The most important characteristic of residual soils is the low strength due to the destruction of the bonds and the cementation of the material from the weathering processes. In certain cases, they appear to have high shear strength, but as they reach saturation the shear strength reduces significantly with zero or very small effective cohesion (Lumb, 1965). Residual soils in Singapore are often a problem during heavy rainfall events since the flow of rainwater into the unsaturated zone results in an increase in the pore-water pressure and a decrease in the shear strength of residual soil (Fredlund & Rahardjo, 1993). As a result, rainfall-induced slope failures frequently occur in tropical areas that are covered mainly with residual soils (Rahardjo et al, 2013).

Three main soil types exist in Singapore Island. The western part of Singapore is predominantly covered by the residual soil from Jurong Formation, the north and central parts of Singapore are covered by the residual soil from Bukit Timah Granite, whereas the eastern sides of Singapore are covered by the residual soil from Old Alluvium (Oliver & Gupta, 2017). Rahardjo et al (2012) carried out soil sampling in 40 locations throughout Singapore island. **Figure 1** shows the main soil formations in Singapore and 40 locations of the soil samplings from previous studies by Rahardjo et al (2012).

2.2. Data preparation

Four (4) different methods were incorporated in Spatial Analyst Tools of ArcGIS to study an appropriate method for the development of the suitability map for the soil sampling locations in Singapore. Prior to spatial analyses, the data input in terms of GIS layer must be prepared correctly to ensure the reliability of the results of the analyses. In this study, five (5) different clasess were used to determine the suitability of each GIS layer, i.e. very low, low, medium, high and very high. Three (3) GIS layers were incorporated in the Spatial Analyst Tool for spatial analyses using four different methods, i.e. Analysis by Weights, Inference Matrix, Fuzzy Overlay Gamma and Per-Cell Statistic Method (PCSM). The first layer is the digital elevation model (DEM) layer which provides the elevation of the slope. The second layers is the slope layer, which is referring to the inclination of the slope. The third layer is associated with the location of the previous soil sampling in Singapore based on the study from Rahardjo et al (2012). Forty (40) locations of soil sampling from Rahardjo et al (2012) were used in this study since all soil samplings were conducted within the slope surface and they were distributed in different formations in Singapore. It is important to use this data since the purpose of this study is to determine the suitability of the soil sampling location for the purpose of development of the slope susceptibility map in the future. The laboratory test results of soil samples from the selected locations will be used in this study for the analyses of rainfall-induced slope failures in Singapore. Toll (1999) observed that the slope failures in Singapore are related to shallow slip surface. Therefore, the determination of soil sampling location in this study only incorporated soil layer. Geological layer is not relevant for the selection of soil sampling location in this study.

The classification of GIS layers with respect to DEM, slope angle and distance to the previous soil sampling locations are presented in **Figure 2**.

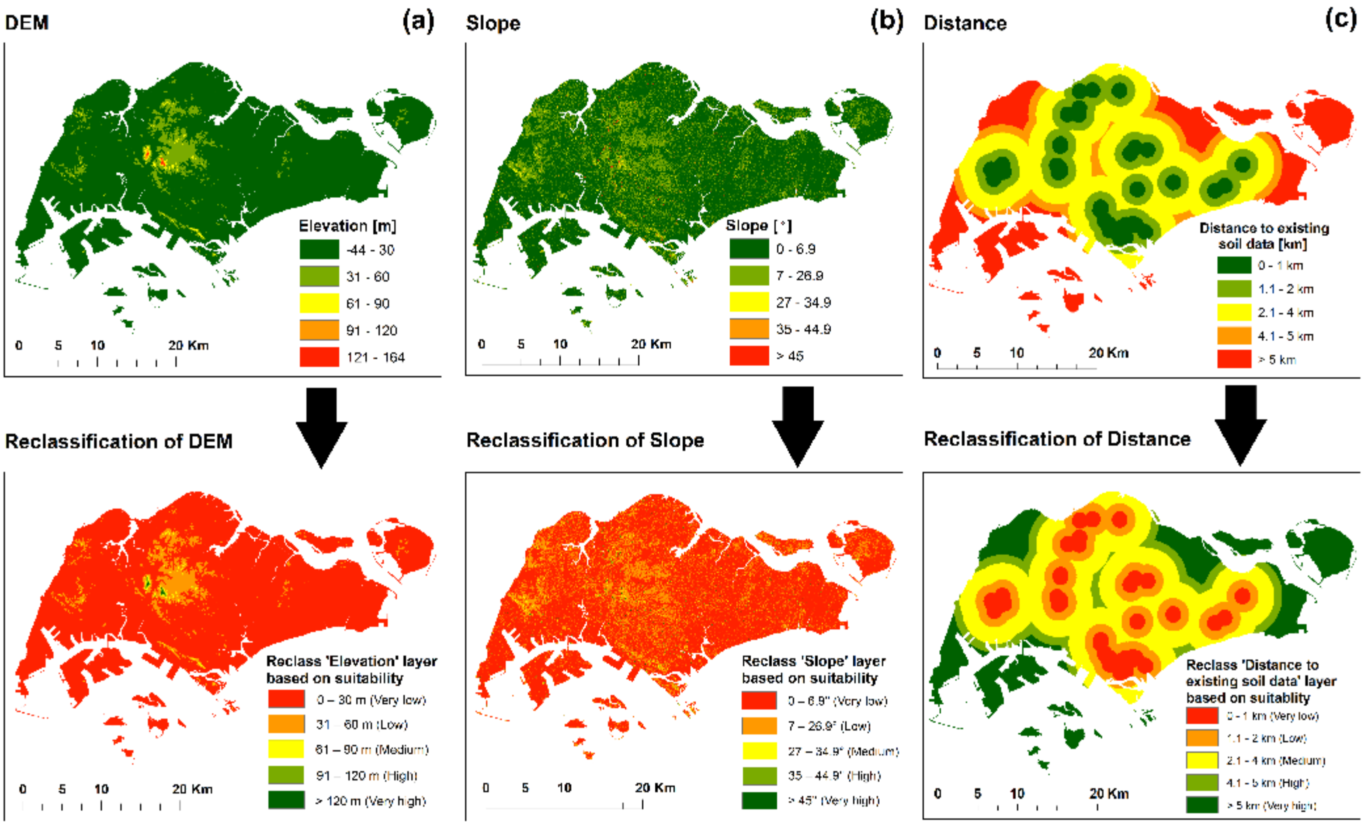

Fig. 2. Classification and reclassification of (a) DEM, (b) Slope angle, and (c) Distance to the previous soil sampling locations

Figure 2 shows that the elevation of Singapore island varies from -44 m to 164 m. The DEM layer was reclassified based on 5 suitability classes with the same interval in each class. Slope located in the high elevation is cosidered to be more prone to environmental conditions (i.e. cracks due to high temperature, high infiltration due to rainfall). Hence, it is very important to have soil sampling in the high elevation. The slope layer was divided into 5 classes as follows: 0^o-6.9^o, 7^o-26.9^o, 27^o-34.9^o, 35^o-44.9^o, >45^o. This classification was based on the condition of slope angle in Singapore. The ground surface is commonly inclined to 7^o to drain the rainwater properly into the main drainage especially during high rainfall periods. The engineered slopes in Singapore are commonly designed with 27^o inclination. Slopes with an inclination higher than 45^o are commonly associated with steep slopes in Singapore. The slope layer was also reclassified into 5 suitability classes with steep slope (angle higher than 45^o) is considered very suitable for the locations of the soil sampling. The GIS layer related to the distance to the previous soil sampling location was classified into 5 classes with the same interval of 1 km in each class. 1 km was adopted in this study since this is the lowest resolution of Singapore raster map.

Table 1 illustrates the classification and the reclassification of each GIS layers based on the suitability areas for soil sampling. The reclassification was necessary because the datasets should have the same range of numbers and the same impact to the final results. Reclassification was conducted by normalizing the raster data between 0 and 1. The reclassification of the raster data was completed with 'Reclassify' function in ArcGIS. The spatial resolution of the layers was set at 10 m^2 (**Table 1**).

Table 1. Values of each parameter used in the spatial analysis and the classes

Suitability for the test sites	DEM (m)	Reclassification of DEM (integer numbers)	Slope (Radian degrees)	Reclassification of Slope (integer numbers)	Distance to the previous test sites (km)	Reclassification of the Distances (integer numbers)
Very low	0 - 30	1	0 – 6.9	1	0 - 1	1
Low	31 - 60	2	7 – 26.9	2	1 - 2	2
Medium	61 - 90	3	27 – 34.9	3	2 - 4.	3
High	91 - 120	4	35 – 44.9	4	4 – 5	4
Very high	121 - 164	5	> 45	5	> 5	5

2.3. Spatial analysis using weights

The suitability map based on spatial analysis using weights was developed by applying certain weightage into DEM, slope and distance to previous soil sampling location layers in the ”Raster Calculator” function in ArcGIS. The weightage of 0.3, 0.3 and 0.4 was applied on the reclassification maps of all layers in ”Raster Calculator” using Equation 1. Those weightages were selected based on the importance of each layer in the spatial analyses (Deszi et al, 2015; Nistor et al, 2015).

$$\text{Suitability} = (\text{DEM} \times 0.3) + (\text{Slope angle} \times 0.3) + (\text{Distance} \times 0.4) \quad (1)$$

The 30% weightage for DEM and slope layers were selected since both factors provided similar contribution into slope stability analyses. The 40% weightage for distance to previous soil sampling location layer was selected since this layer had the highest impact in the spatial analyses. This layer was significantly required to avoid the overlapping between the new soil sampling location in this study and the previous soil sampling location from Rahardjo et al (2012).

2.4. Spatial analysis using inference matrix method

The suitability map based on spatial analysis using inference matrix method was generated using predefined overlay procedure with 5 x 5 matrices (i.e. very low, low, medium, high and very high). Two steps were required in the development of the suitability map based on three required GIS layers, DEM, slope and distance to previous soil sampling location layers.

The first step is to establish the classification for the suitability of the terrain for soil sampling based on relationship between elevations and slope layers.

The second step is to generate the suitability map for the new soil sampling in this study based on the relationship between the suitability of the terrain for soil sampling and the distance to the previous soil sampling location layer.

The inference matrix to establish the suitability of the terrain for soil sampling is presented in **Figure 3**. The inference matrix to develop the suitability map of the new soil sampling location in this study is presented in **Figure 4.**

		Slope (degree)				
		0 – 6.9	7 – 26.9	27 – 34.9	35 – 44.9	> 45
	Suitability	Very low	Low	Medium	High	Very high
Elevation (m)						
≤ 30	Very low	Very low	Very low	Low	Low	Medium
31 - 60	Low	Very low	Low	Low	Medium	Medium
61 - 90	Medium	Low	Low	Medium	Medium	High
91 - 120	High	Low	Medium	Medium	High	High
> 120	Very high	Medium	Medium	High	High	Very high

Terrain suitability for test sites location				
Very low	Low	Medium	High	Very high

Fig. 3. The inference matrix to establish the suitability of terrain for soil sampling.

Distance to previous sites (km)		Suitability	Terrain data: Class 1 (Very low)	Class 2 (Low)	Class 3 (Medium)	Class 4 (High)	Class 5 (Very high)
Close nearest	0 - 1	Very low	Very low	Very low	Low	Low	Medium
Nearest	1 – 2	Low	Very low	Low	Low	Medium	Medium
Moderate nearest	2 - 4	Medium	Low	Low	Medium	Medium	High
Far	4 - 5	High	Low	Medium	Medium	High	High
Very far	> 5	Very high	Medium	Medium	High	High	Very high

Integrated suitability for test sites location				
Very low	Low	Medium	High	Very high

Fig. 4. The inference matrix to develop the suitability map for the new location of the soil sampling.

2.5. Spatial analysis using Fuzzy Overlay Gamma

The suitability map based on Fuzzy Overlay Gamma spatial analysis was developed using an automatic approach in ArcGIS. The 'Fuzzy Overlay Gamma' was selected because the method yields the values between 0 and 1. The required variables in the analysis were 'Fuzzy Product' and 'Fuzzy Sum' (ESRI, 2013). Both of these variables are dependent to the power of gamma. The general function incorporating both variables is presented in Equation 2. The general equation used in Fuzzy Overlay Gamma spatial analysis is presented in Equation 3.

$$\mu(x) = (\mathrm{FuzzySum})^{\gamma} \times (\mathrm{FuzzyProduct})^{1-\gamma} \qquad (2)$$

$$\mathrm{fuzzyGammaValue} = \mathrm{pow}(1 - ((1 - \mathrm{arg1}) \times (1 - \mathrm{arg2}) * \ldots), \mathrm{Gamma}) \times \mathrm{pow}(\mathrm{arg1} \times \mathrm{arg2} \times * \ldots, 1 - \mathrm{Gamma}) \qquad (3)$$

The gamma value of 1 produces an output equal to 'fuzzy Sum'. The gamma value of 0 provides an output equal to 'Fuzzy Product'. The gamma value between 0 and 1 generates different output of 'Fuzzy Overlay Gamma' as compared to the output of other fuzzy methods, e.g. 'fuzzy Or' or 'fuzzy And'. The Fuzzy Overlay Gamma can be used when the expected values should be greater than fuzzy Product and less than fuzzy Sum. The final suitability map for determination of the new soil sampling location in this study can be classified into five classes similar to the suitability map obtained from other methods of spatial analyses.

2.6. Spatial analysis using per-cell statistic maximum method

The suitability map based on spatial analysis using per-cell statistic maximum (PCSM) method was produced by selecting the maximum values from each GIS layer of DEM, slope and distance to the previous soil sampling location layers. Prior to the analysis, all three layers should be superimposed correctly to ensure the accurate calculation of maximum value of each cell from all layers. All cells in the suitability map should be independent of all cells in each GIS layer.

3. RESULTS

The suitability map for the soil sampling locations in Singapore was developed based on four methods using Spatial Analyst Tools in ArcGIS. The results from analysis using the spatial analysis by weights indicated that the high and very high suitability for the soil sampling are located in the small areas in the central, north western and north eastern parts of Singapore. The central parts of Singapore was very suitable for soil sampling since this area was located in high elevation and majority of slopes in this area were steep. Few locations with high suitability for soil sampling could also be found in the western, southern, and eastern parts of Singapore. However, these locations are close (within 1-1.5 km) to the previous soil sampling locations. The areas with medium suitability extended mostly in the north western, eastern, north eastern and south western parts of Singapore with a distance longer than 5 km to the previous soil sampling locations. In general, majority of areas have low suitability for new soil sampling locations based on the spatial analysis by weights. All cells in these areas were located within a distance of 1 to 5 km to the previous site investigation locations. **Figure 5** shows the suitability map for soil sampling locations obtained from spatial analysis by weights. It can be seen that the central, the north western, north eastern and eastern parts of Singapore are suitable for new soil sampling locations.

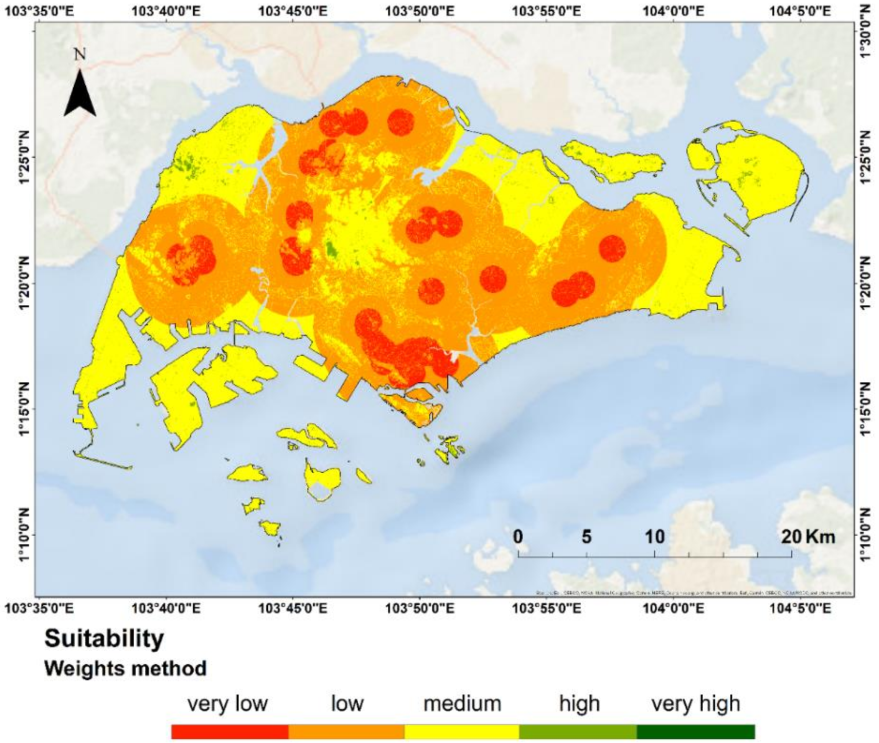

Fig. 5. Suitability Map for soil sampling locations in Singapore obtained from spatial analysis using weights. Background image source: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

The results of spatial analysis using the inference matrix method indicated that only very few areas were associated with high and very high suitability for new soil sampling locations. Majority of areas produced from the spatial analysis using this method were associated with very low, low and medium suitability for soil sampling. The areas with very high and high suitability for soil sampling were located in the north western, north eastern and south western parts of Singapore (**Fig. 6**).

The spatial analysis results using this method also shows that the areas with a distance up to 1 km to the previous soil sampling locations were classified as very low suitability for new soil sampling locations. The areas loacted at the distance between 1 and 5 km to the previous soil sampling locations were classified as low suitability for new soil sampling locations. The areas located at a distance higher than 5 km to the previous soil sampling locations were classified as moderate suitability for new soil sampling locations. **Figure 6** shows that the eastern, north western and north eastern of Singapore are suitable for new soil sampling locations.

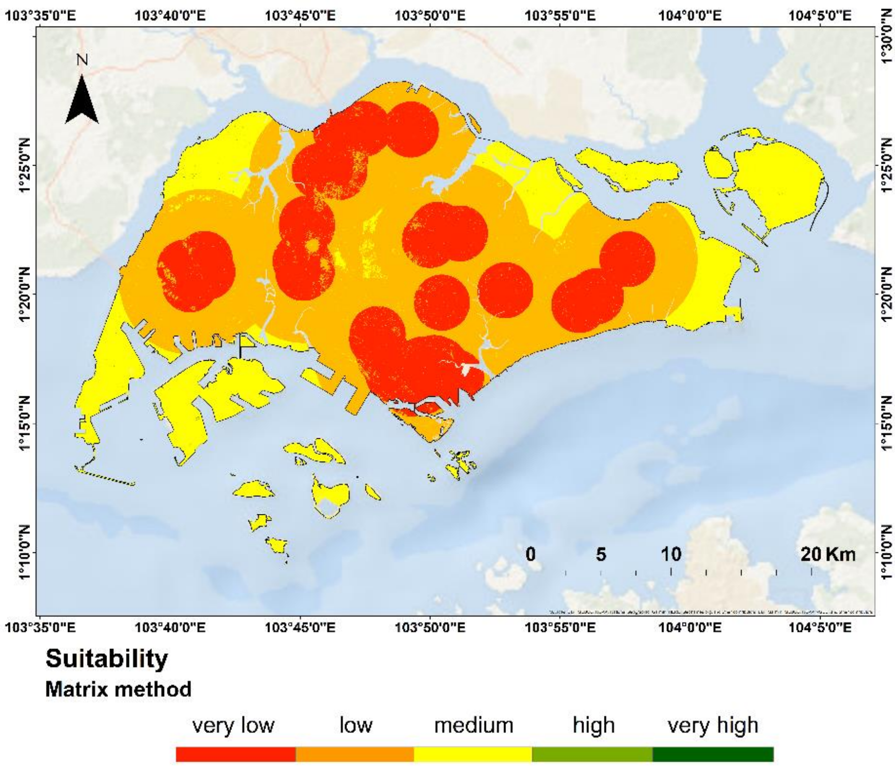

Fig. 6. Suitability Map for soil sampling locations in Singapore obtained from spatial analysis using the inference matrix. Details of this map could be seen in the **Figure 7**. Background image source: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

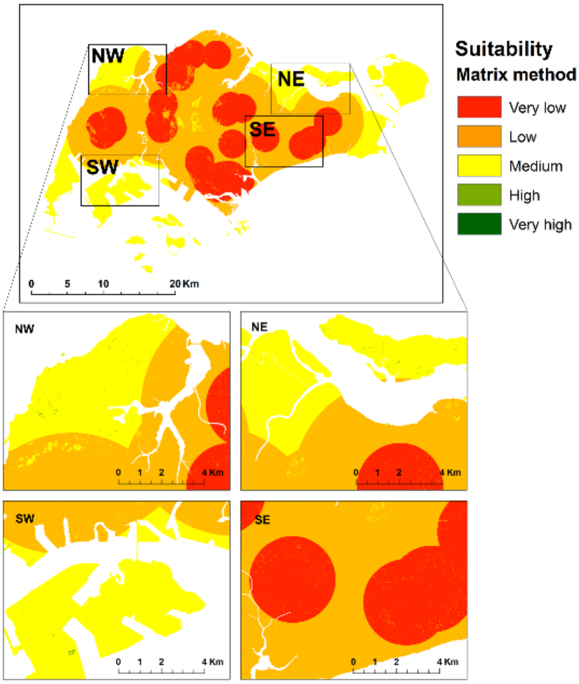

Fig. 7. Details of Suitability Map carried out using the inference matrix. Details of this map could be seen in the Supplementary material 1. Background image source: ESRI, Garmin, GEBCO, NOAA NGDC, and other contributors.

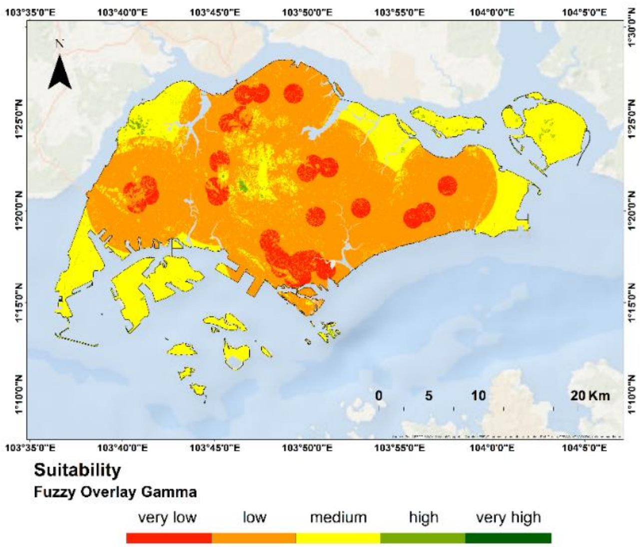

Fig. 8. Suitability map for soil sampling locations in Singapore obtained from spatial analysis using Fuzzy Overlay Gamma. Background image source: ESRI, Garmin, GEBCO, NOAA NGDC, and other contributors.

The analysis using Fuzzy Overlay Gamma method indicated that majority of areas in Singapore was classified as low suitability for new soil sampling locations. **Figure 8** shows that very few areas with high and very high suitability for new soil sampling locations were located in the north western and central parts of Singapore. The areas with medium suitability were located in the northeastern and southwestern parts of Singapore. The areas with very low suitability were located within a distance of less than 1 km to the previous soil sampling locations in Singapore. The suitability map from this method shows that the eastern, north western and north eastern of Singapore are suitable for new soil sampling locations.

The suitability map based on PCSM indicated that areas with very high and high suitability were distributed in the northern, western, southwestern, eastern and central parts of Singapore (**Fig. 9**). The areas with a distance of 1 km to the previous soil sampling locations were classified as low suitability. The areas with a distance between 1 and 4 km to the previous soil sampling locations were classified as medium suitability. Very few areas with very low suitability were observed in the southern part of Singapore. The suitability map from this method shows that only the southern part of Singapore is not suitable for new soil sampling location.

4. DISCUSSIONS

The results of the spatial analyses using four different methods in the Spatial Analyst Tools of ArcGIS indicated that the suitability map from the spatial analysis by weights is very close to that from the spatial analysis using Fuzzy Overlay Gamma. This is attributed to the similar algorithm used in both methods which depend on the weightage of each layer and the summation of all layers.

The areas with high and very high suitability were easily defined from the suitability map obtained from both methods. Eleven (11) to one hundred (100) soil sampling locations can be selected from the suitability map. The suitability map based on spatial analysis using the inference matrix method provided only few suitable locations for soil sampling. This limited results were attributed to the reduction of the number of cells with high suitability as compared to the cells in the suitability map from spatial analysis using other methods. The spatial analysis using the inference matrix was useful to determine the new soil sampling locations when the previous data were very limited (less than 10 data points).

The spatial analysis using the PCSM method produced the suitability map for a large areas with high and very high suitability, especially in the central, northeastern and northwestern parts of Singapore. These areas were located at a distance of greater than 5 km to the previous soil sampling locations. These areas were also located in the high elevation and with steep slope angle.

The suitability map from the spatial analysis using the PCSM method provided higher distinct differences between each suitability classes as compared to that from the spatial analysis using other methods since the PCSM method extracted the maximum values from each GIS layer of DEM, slope and distance to the previous soil sampling locations. The PCSM method is very suitable for determination of high number of soil sampling locations.

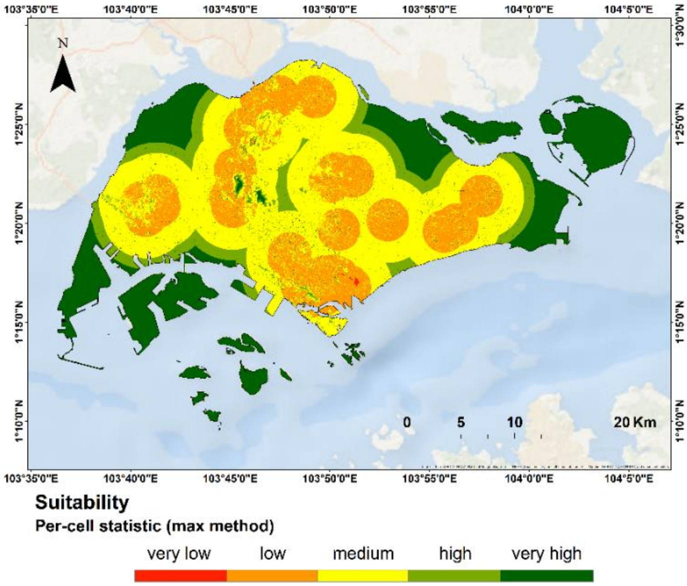

Fig. 9. Suitability Map for soil sampling locations in Singapore obtained from spatial analysis using per-cell statistics maximum (PCSM). Background image source: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

5. CONCLUSIONS

Based on the data in this study, the following conclusions can be withdrawn:

- Spatial analyses for development of suitability map for soil sampling locations using four methods in the Spatial Analyst Tools of ArcGIS, i.e. spatial analysis by Weights, spatial analysis using the inference matrix, spatial analysis using Fuzzy Overlay Gamma and spatial analysis using per-cell statistic maximum have been presented and discussed.
- The spatial analysis by weights and Fuzzy Overlay Gamma are suitable for determination of soil sampling locations up to 100 data points.
- The spatial analysis using the inference matrix is suitable for determination of limited number of soil sampling locations (up to 10 data points).
- The spatial analysis using the PCSM method is suitable for determination of large number of soil sampling locations (more than 100 data points).
- Based on four methods used in the spatial analyses, the northwestern, the southwestern, central and the eastern parts of Singapore are considered as the suitable locations for new soil sampling.

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