# SPATIAL VARIABILITY OF SOIL PHYSICAL PROPERTIES IN SOUTHERN MANKAYAN, BENGUET, PHILIPPINES

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**KEY WORDS**: spatial variability, inverse distance weighting, soil physical properties, landslide, mankayan mineral district

**ABSTRACT:**

Hydrothermal alteration in the Mankayan Mineral District in Benguet, Philippines, has had a significant impact on the soil characteristics. Thus, soil characterisation in landslide zones offer useful insights on the nature of slope failure and provide baseline data that may be used with susceptibility mapping and hazard zonations. The study elucidated the physical characteristics of the soils in the southern portion of Mankayan and mapped out the spatial distribution in the area. High sand and low clay content cause low slope stability due to the low water retention in soil, low plasticity, and low shear strength of materials while the resulting porosity led to poor drainage. Results show that the soil's physical properties, whereas most rock units have been affected by alteration, have caused rock deterioration that eventually led to slope failures. The presence of various parent material in the study site influenced the distribution of soil physical properties, specifically the influence of dacite on the Atterberg limits in the central area of southern Mankayan.

## 1. INTRODUCTION

The Philippine archipelago's geographic location predisposes the country to perennially experience meteorological related hazards. Aside from the about 20 tropical cyclones every year, the country also experiences intertropical convergence zones, southwest, and northeast monsoons (PAGASA, n.d.). In the past decade, extreme events have triggered landslides and have had tremendous socio-economic effects and loss of lives (e.g., Yumul et al., 2010). The majority of landslide incidents in the Philippines are caused by intense and/or prolonged rainfall on steep slopes that are frequently made up of highly fractured, poorly indurated, and heavily worn rock elements (e.g., Nolasco-Javier et al., 2015; Abancó et al., 2021). Current researches in landslide susceptibility mapping and assessments in the Philippines only include geology (e.g. Saldivar-Sali and Einstein, 2007; Padrones et al., 2017) and structures (e.g. Eco et al., 2015; Luzon et al., 2016) as causative factors as well as geomorphological parameters. However, there is a paucity of studies related to the effect of hydrothermal alteration in the occurrence of landslides in the Philippine setting and the influence of alteration in the overlying soil materials (e.g., Opiso et al., 2015).

### 1.1. Effects of alteration in soil physical properties

Previous studies in altered rocks state that alteration could either result to rock properties improvement (e.g., consolidation, strengthening, a decrease of porosity and permeability, and a removal of hygroscopic moisture in the rock) or deterioration (e.g., formation of secondary porosity and permeability, a decrease of density and elastic modulus, weakening, and formation of hygroscopic moisture) (Frolova et al., 2014). Moreover, the alteration of the rocks results in the formation of clay minerals and consequently changes the physical properties of previously competent rock units (Frolova et al., 2015). These predisposing factors that might cause landslides are inherent in a highly-mineralized area like in the Mankayan Mineral District (MMD; Claveria, 2001; Sajona et al., 2002). For instance, on August 22, 2015, a landslide that occurred during the onslaught of Typhoon Ineng (internationally known as Goni) covered the small-scale miner's shanties in Sitio Elizabeth, Brgy. Taneg in Mankayan, Benguet. This incident resulted in the death of 16 miners temporarily living in their shanties that were covered by the landslide debris from a collapsed mountain (GMA News online, 2015; Lapniten, 2015). Several other landslide occurrences with casualties were reported in the area and in some areas, the presence of small and large scale mining industries has been put to blame for such disasters. The fractured nature of the rocks which served as conduits of hydrothermal fluids that carried the metal deposits and the consequent alteration of rocks are some of the controlling factors that caused these landslides. This is one of the reasons why the occurrence of landslides is spatially related to areas with active mining activities.

### 1.2. Spatial variability

The spatial variability of soil properties generally determines the change of a soil property's magnitude in space and is observed at different spatial locations on the land surface, or at some soil depths. However, certain environmental factors such as parent material, topography, climate, vegetation, and anthropogenic disturbances have a considerable impact on the spatial variability of soil properties in an ecosystem (Wendroth et al., 2011). The combined action of physical, chemical, and biological processes as well as anthropogenic land use patterns, which vary in space and time across the landscape and influences the scales of spatial variation between different soil properties, since the processes that cause variability may occur at different scales (Peukert et al., 2012).

Soil spatial variability is frequently overlooked but this aspect determines the distribution of soil properties in a certain area. In the past decades, numerous studies have documented the physico-chemical properties of soil in Benguet, Philippines such as the study of Lurean et al. (2016) on physical and chemical properties of soils as well as the traces of toxic heavy metals (i.e., mercury and lead) in agro-ecological zones in La Trinidad,

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Buguias, and Atok, Benguet. However, looking into the spatial variability of soil physical properties in Barangay Taneg and the generation of spatial variability maps would be the first of its kind in the municipality and in the province as a whole.

The understanding of soil properties in areas with occurrences of landslides and the accurate estimation of spatial distribution and variability is important in understanding mechanisms of slope failures and how this could be applied in areas with similar geologic make up, particularly in mineralized zones. The results of this study would serve as primary data for the local government units to develop plans and strategies related to disaster-risk reduction. Moreover, there is also a paucity of soil related data in the country, particularly since a lot of the soil maps still contain undifferentiated mountain soil, thus spatial distribution analysis could provide valuable information that could augment the need for soil data.

## 2. METHODS

### 2.1. Study area

The study area, the MMD, is located in the western part of Luzon Island (Figure 1). There are 8 reported mineral deposits with operating mines and exploration prospects in MMD (Jabagat et al., 2023 and references therein). Moreover, the different alteration zones surrounding MMD are discussed in detail in the works of Cooke et al. (2011) and Chang et al. (2011). The lesser known Suyoc Au-Cu deposits in the southern part of MMD has been recently reported as an epithermal vein-type with a potential presence of porphyry Cu and high sulfidation epithermal mineralization (Soberano et al., 2021; Arellano et al., 2021). All of these mineralizations have caused hydrothermal alteration in the surrounding host rocks.

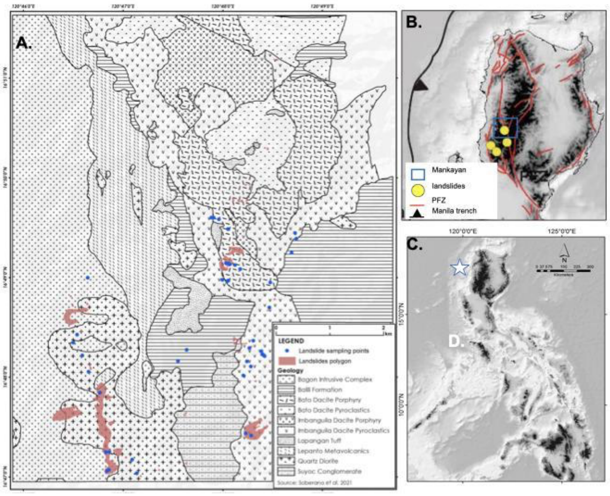


**Figure 1**. A) Lithologic units in Mankayan, Benguet showing the extent of the different landslides in the area (adopted from Soberano et al., 2021). B) The study area is part of the Mankayan Mineral District which is located in the northern part of the Philippines (C).

### 2.2. Sampling and Laboratory methods

Sampling and field mapping was carried out from November 24 to December 02, 2018 and July 17 to 24, 2019. Samples were collected from landslide scarps (Figure 2A, B) and road cuts with slope failures in the barangays of Taneg and Palasaan in Mankayan, Benguet. A total of 100 samples were analyzed for this study. Representative samples were selected for spatial analyses. These samples were reclassified based on the parent material lithology wherein the main groups observed were dacite and dacite pyroclastics, quartz diorite and tonalite, and sedimentary and volcaniclastic rocks (Table 1).

Soil samples were subjected to physical property analyses which were carried out at the Soils Laboratory of the Institute of Renewable Natural Resources, University of the Philippines, Los Baños, Laguna. Analyses include bulk (undisturbed core method) and particle densities, particle size (Hydrometer method; PCARR 1980), and Atterberg limits (plastic, sticky and liquid limits; Atterberg, 1911).

### 2.3 Statistical and GIS analyses

With the data readily available, Inverse Distance Weighting (IDW) method was used to represent the spatial distribution as well as the correlation of regionalized variables on a certain scale. The interpolations were performed using geostatistical and spatial analyst tools in ArcGIS Pro 3.1 in order to generate spatial distribution of soil physical properties in southern Mankayan. IDW does not require solving any system of equations for the weights since it rests on a priori assumption of change of weights with distance-decay (Ligas et al., 2022). The cross-validation technique was applied using the geostatistical analyst feature in ArcGIS Pro. Regression models were produced to compare the interpolated values with the actual measured values within the inverse distance optimized model.

## 3. RESULTS AND DISCUSSIONS

Landslides in the study sites are mostly rotational (e.g. Figure 2A,B,C) but with few areas with translational movement. Few rock slides were noted along the road. Hydrothermal alterations observed are argillic and silicification were noted (Figure 2B,C,D) and sometimes interlayered with Fe-rich deposits. To note, among the largest and most extensive landslides are areas with argillic and silicic alterations. Moreover, silicic alteration resulted in rock rock deterioration in the study area wherein fractures were filled with quartz minerals (Figure 2D). However, where quartz -alunite-sulfide alterations were observed (e.g., Mohong Hill, Figure 2B), rock consolidation was more dominant (e.g., Frolova et al., 2014). Analysis of the landslide scarps extent through the number of pixels with landslides vis-a-vis the total number of pixels per rock type (Figure 1A) showed that areas underlain by quartz diorite have the highest occurrence of landslides (62.75%), followed by dacite (22.67%) while other rock units (volcaniclastics of Balili Formation, mudstone, and conglomerate) comprised 14.57%.

Soil compositions in the study area were identified to be underlain mostly of undifferentiated mountain soil, which are located in difficult-to-reach mountainous regions, and Guinaoang Loam, a sandy loam that is soft and crumbly but slightly sticky when wet (Carating et al., 2014). Moreover, six geologic formations encompass the study area, namely; Balili Formation, Bato Dacite Porphyry, Imbaguila Dacite Pyroclastics, Lapangan Tuff, Lepanto Metavolcanics, and Suyoc Conglomerate (Soberano et al., 2021; Arellano et al., 2021). Most of these rock formations have a volcanic parent material that exhibits a fine-grained texture, particularly the diorite and dacite parent materials found in the Balili Formation, Bato Dacite Porphyry, Imbaguila Dacite Pyroclastics, and the Lapangan Tuff.

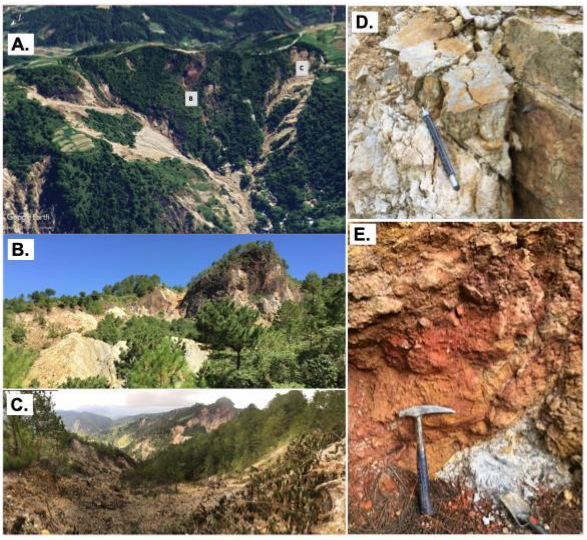


**Figure 2**. A) Map showing landslides in Palasaan (Google Earth, earth.google.com/web/). Inset shows the location of Figure 2B,C. B) Argillic alteration surrounding Mohong Hill, which is composed of quartz-alunite minerals. C.) Scarps in one of the reactivated landslides in the area in 2019 showing silicic and argillic alterations. D. Silicic alteration along fractures of the basement Lepanto metavolcanics. E. Interlayered argillic and Fe-rich soils.

### 3.1. Soil physical properties

Results show that bulk and particle densities range from 0.80 to 2.3, with soils from quartz diorite and tonalite parent rock materials having the highest mean densities. Particle density values are slightly higher in some samples due to the presence of heavy minerals such as pyrite. The computed pore spaces have relatively low mean percentage (i.e. 28%). Generally, the porosities of the soil samples are lower than 50%; these are attributed to low clay content (and consequently high sand content) and high bulk density values (Table 1). The landslides are caused by slow water percolation and poor drainage, while high sand percentage and low clay content resulted in low water retention and decreased slope stability due to reduced cohesion forces and smaller amounts of binding between particles (Del Potro & Hürlimann, 2009; Frolova et al., 2014).

The sand and clay fractions of the soils from landslide areas were compared among different parent rock materials. Results show that high sand content is common among the samples even with mudstone samples, wherein the dominant composition should have been clay fractions. This is due to the intensive silicic alteration in the study area, thus most of the original minerals were replaced by quartz.

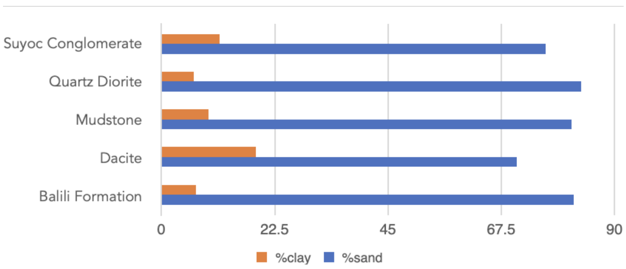


**Figure 3.** Comparison of the different soils from their various parent materials lithologies.

| Lithology \| Geologic Formation | Bulk Density (g/cm$^3$) | Particle Density (g/cm$^3$) | Pore Space (%) | clay content (%) | sand content (%) |
|---|---|---|---|---|---|
| dacite and dacite pyroclastics | R:0.80-2.40 (n=26); M: 1.59 | R:1.17-3.33 (n=37); M: 2.36 | R:3.05-64.79 (n=26); M: 28.98 | R:0-34.04(n=43); M: 14.63 | R:40.43-90.22 (n=43); M: 73.43 |
| quartz diorite/tonalite | R:1.26-2.46 (n=9); M:1.81 | R:2.08-2.86 (n=21); M:2.60 | R:9.74-48.92 (n=9); M:28.33 | R: 1.68-33.40 (n=23); M:12.70 | R:28.27-94.59 (n=23); M:70.95 |
| sedimentary/volcaniclastic rocks \| Suyoc Conglomerate | R:1.31-2.53 (n=12); M: 1.78 | R:1.61-3.18 (n=21); M:2.55 | R:4 - 51.11 (n=12); M:23.65 | R:0-37.89 (n=26);M:12.38 | R:38.19-91.4 (n=26); M:74.82 |

**Table 1.** Densities (bulk and particle), porosity, and grain sizes (clay and sand) of the soil samples in landslide areas in Mankayan, Benguet. The samples are arranged according to rock types. Range (R) and Mean (M) values are shown.

The plasticity index of the samples ranged from 0.70 to 35.48 which are classified as low to intermediate. The quartz diorite and tonalite samples have the lowest mean value (7.06) while sedimentary rocks yielded the highest mean value (13.64). Comparison between soil texture (grain size, Figure 4A) and lithology (Figure 4B) vis-a-vis plasticity showed no dominant trend. Moreover, these samples have lower plasticities compared to Mt. Makiling samples, which were least affected by alteration (Padrones et al., 2020). The Atterberg limits are relatively low wherein sticky and plastic limits are <50% for all samples with various parent materials (Figure 4C,D). This is due to the low clay content but high sand contents in the soil samples. The resulting soil materials affected by hydrothermal alteration affected the grain size distribution and consequently caused low shear strength which eventually caused slope failures in the study area.

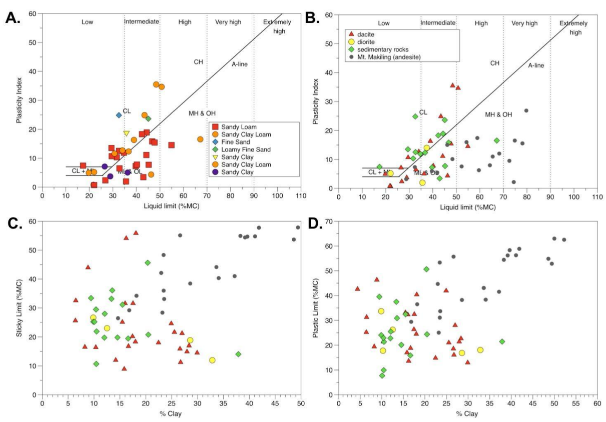

**Figure 4.** Plasticity chart showing the different plasticity of the samples, which are arranged based on soil texture (A) and rock type (B). The sticky (C) and plastic (D) limits of the samples vis-à-vis the clay content shows sporadic distribution, unlike the Mt. Makiling samples which exhibit a positive trend between the clay content vis-à-vis sticky and plastic limits.

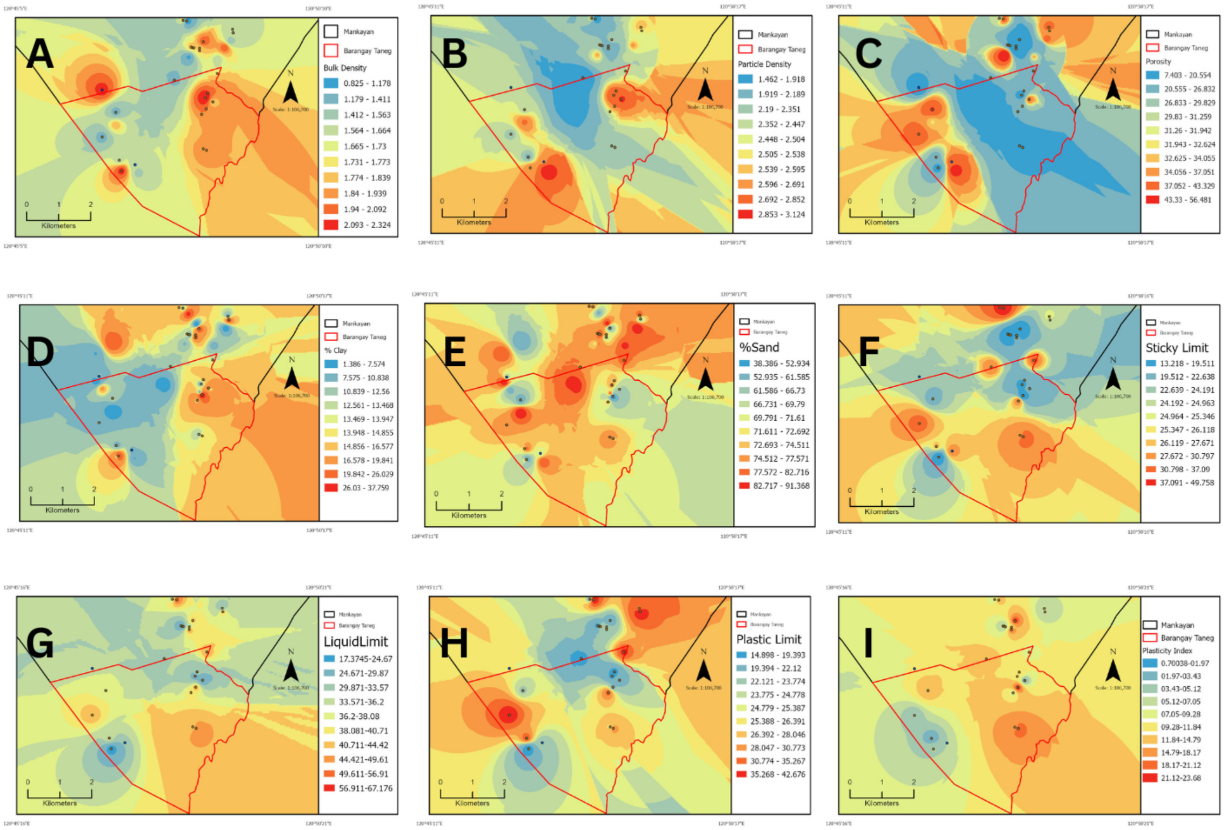


**Figure 6.** Spatial distribution maps of bulk density (A), particle density (B), porosity (C), clay content (D), sand content (E), sticky limit (F), liquid limit (G), plastic limit (H), and plasticity index (I).

Pearson's correlation coefficient of the different physical properties showed strong positive correlation between plastic, sticky and liquid limits, and plasticity index while strong negative correlations were noted between porosity and bulk density and % sand and % clay (Figure 4). Moreover, sand content is negatively correlated with bulk and particle densities, liquid limit, and plasticity index.

| R | %sand | BD | PD | PS | %clay | SL | PL | LL | PI |
|---|---|---|---|---|---|---|---|---|---|
| %sand | 1.00 | | | | | | | | |
| BD | -0.24 | 1.00 | | | | | | | |
| PD | -0.08 | 0.28 | 1.00 | | | | | | |
| PS | 0.32 | -0.73 | 0.44 | 1.00 | | | | | |
| %clay | -0.88 | 0.30 | 0.06 | -0.44 | 1.00 | | | | |
| SL | 0.24 | -0.61 | -0.16 | 0.34 | -0.33 | 1.00 | | | |
| PL | 0.16 | -0.46 | -0.34 | 0.18 | -0.23 | 0.61 | 1.00 | | |
| LL | -0.26 | -0.21 | -0.30 | -0.36 | 0.21 | 0.61 | 0.61 | 1.00 | |
| PI | -0.42 | 0.10 | -0.20 | -0.49 | 0.42 | -0.14 | -0.30 | 0.54 | 1 |

**Figure 5.** Result of Pearson's correlation analysis. Abbreviations are BD = bulk density, PD = particle density, PS = pore space/porosity, SL = sticky limits, PL = plastic limits, LL = liquid limits, and PI = plasticity index.

### 3.2. Spatial variability

Nine (9) soil physical properties were mapped out and interpolated using inverse distance weighting method to determine the spatial distribution in southern Mankayan (Figure 6). The resulting density values found in the distribution maps correlates to the amount of soil textural particles found in the study area. Bulk density (Figure 6A) is one indicator of soil compaction. In general, the region has values higher than 1.33 g/cm3, indicating soil compaction; however, the central area of southern Mankayan exhibits lower values indicating loose, porous soils. The mapped particle density values (Figure 6B) were consistent to the measured values of porosity (Figure 6C) wherein the western side of the area was observed to have higher measured values for both variables suggesting the presence of heavy minerals, which was identified to be pyrite.

Clay content (Figure 6D) in the region generally lies below the acceptable threshold of 30%, except for certain areas of concentrations which exceed the acceptable values. Sand content (Figure 6E) however, is observed to have higher values where the values of particle density and porosity were measured. Atterberg limits in southern Mankayan consistently have low measured values in the central areas due to the dacite parent material observed in the Imbaguila Dacite Pyroclastics formation. Regression models (Figure 7) were produced from the inverse distance optimized models in order to validate the accuracy of interpolated values in the variability maps by comparing actual measured values on physical sampling sites to the predicted values using the cross-validation technique. The regression model for particle density (Figure 8C) was deemed as the most accurate interpolation among the distribution maps since the predicted values have a lower margin of error from the measured value when taken out as part of the cross validation. The limitation behind the low accuracy of interpolation of the distribution maps can stem from the number of sampling sites and the even distribution of sampling points in the study site since inverse distance weighting method, in essence, relies on the weighted average of neighboring values, assigning larger weights to closer points (Ligas et al., 2022).

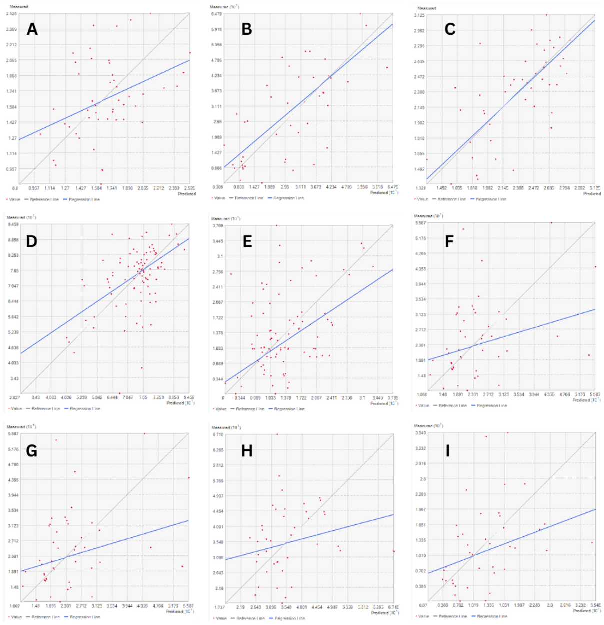

**Figure 7.** Regression models for bulk density (A), porosity (B), particle density (C), sand content (D), clay content (E), plastic limit (F), sticky limit (G), liquid limit (H), and plasticity index (I).

Generation of maps reflecting the soil physical properties play a pivotal role in the development of policies, plans, and strategies aimed at enhancing land use efficiency, elevating soil quality, and promoting ecological protection initiatives particularly when there is paucity in the availability of such data. These maps serve as invaluable tools which provide essential insights into the spatial distribution and variability of soil characteristics and facilitate informed decision-making processes by illuminating the intricate details of the terrain. Furthermore, the produced maps act as surrogate sources of crucial information, in the absence of extensive, ground-level soil surveys, that bridge the knowledge gap and offer a comprehensive overview of soil attributes across vast landscapes.

## 4. CONCLUSIONS

Analysis of landslides using the total number of pixels with landslides in Mankayan, Benguet per rock type showed that areas underlain by quartz diorite lithology have the highest occurrence of landslides, followed by dacite. In terms of soil physical characteristics, the samples are generally composed of sand particles with the highest values at 94%. This property consequently resulted in low porosity and low Atterberg limits. The sticky and plastic limits of the samples vis-à-vis the clay content show sporadic distribution. The plasticity index of the samples is lower than the plasticity of Mt. Makiling soils. Silicic alteration was observed to have affected the dacites, quartz diorites, and some of the sedimentary units which in turn, resulted in high sand and low clay content. This caused low slope stability due to the low water retention in soil, low plasticity, and low shear strength of materials while the resulting porosity led to poor drainage. Results show that the soil's physical properties, whereas most rock units have been affected by alteration, have implications for the landslide occurrences in Mankayan, Benguet. The variability of soil physical properties in southern Mankayan was impacted by the presence of diverse geologic formations and parent materials, with dacite noticeably affecting the Atterberg limits in the study site. The spatial variability maps generated serve as groundwork primary data for the classification and identification of physical properties and characteristics of the undifferentiated mountain soil prevalent in a significant portion of southern Mankayan. Moreover, the precision of interpolation through inverse distance weighting is significantly contingent upon the quantity and spatial arrangement of sampling sites within a specific area. This reliance stems from the method's utilization of a nearest neighbor mechanism, where closer points are accorded greater weights during the interpolation process. Hence, the accuracy and reliability of the interpolation outcomes are intricately tied to the careful consideration of both the number and strategic distribution of these sampling sites, making them vital factors in academic research and geostatistical analyses.

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