Investigating the Impact of Lithology and Lineament Structures to the Drainage Morphometry of Carrascal Watershed, Surigao Del Sur, Mindanao, Philippines Using Correlation and Principal Component Analyses

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Investigating the Impact of Lithology and Lineament Structures to the Drainage Morphometry of Carrascal Watershed, Surigao Del Sur, Mindanao, Philippines using Correlation and Principal Component Analyses

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Abstract: *The impact of lithology and lineament structures to the drainage morphometry of the Carrascal watershed, Surigao del Sur, Mindanao Island, Philippines were examined to determine the drainage network evolution of the area. Interferometric Synthetic Aperture Radar Digital Elevation Model (IfSAR DEM) were utilized for lineament extraction, and the lithologic map was digitized from existing geologic maps in ArcMap 10.8. Linear, aerial, and relief aspects of drainage morphometry were given focus on this study. Principal Component Analysis (PCA) identified key parameters—basin length, basin relief, circularity ratio, drainage texture, and bifurcation ratio—as influential in the drainage system. The significant correlations of morphometric parameters to the lithology and lineament structures in the watershed suggest that geologic structures play a major role in shaping the hydrological characteristic and the geomorphology of Carrascal watershed. These insights are valuable for government agencies to enhance watershed conservation, planning, development and hazard risk assessment strategies.*

Keywords: Sambunotan, Watershed Management, Hydrological Assessment, Geologic Mapping

1. INTRODUCTION

Watersheds are integral hydrological units shaped by surface geology, climate dynamics, and hydrological processes, collectively influencing their morphological and hydro-morphometric characteristics. Understanding these features is critical for effective watershed management and conservation efforts. The discipline of drainage morphometry provides essential insights into watershed hydrology, offering valuable data on basin characteristics and responses to environmental changes [1].

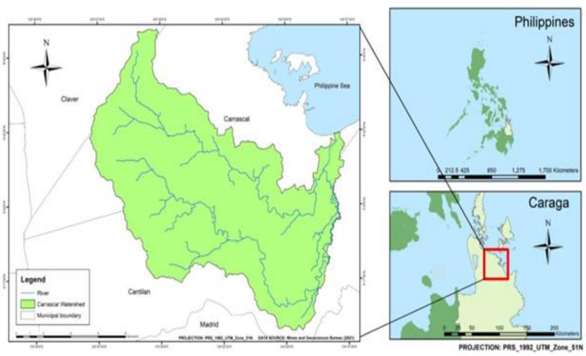

Fig. 1. Location map of Carrascal watershed, in the province of Surigao del Sur, Mindanao Island, Philippines.

The Carrascal watershed (Fig. 1) is situated in the municipalities of Cantilan and Carrascal within the province of Surigao del Sur, located in the Caraga Region of Mindanao, Philippines. This watershed encompasses a total area of approximately 166.4 square kilometers and is intricately subdivided into 49 distinct sub-basins. It spans a diverse topography and hydrography as it drains predominantly from the north towards the eastern direction, with its drainage network extending to the borders of the town of Carrascal.

The watershed exhibits a significant range of elevation, varying from as low as 5 meters above sea level at its lowest points to a remarkable 1162 meters above sea level at its highest peaks. This variation in elevation contributes to a complex and dynamic landscape, influencing both the hydrological processes and the morphological characteristics of the area. The substantial elevation gradient plays a crucial role in shaping the watershed's drainage patterns, erosion processes, and overall watershed management strategies. Furthermore, the diverse elevation also affects microclimatic conditions within the watershed, leading to varied precipitation patterns and soil moisture levels that further influence local vegetation and wildlife habitats. The Carrascal watershed's expansive area and varied elevations provide a unique opportunity to study the interplay between geological formations, lineament structures, and hydrological dynamics. Its broad spatial extent and pronounced elevation differences create a complex landscape that influences its geological and hydrological characteristics in significant ways.

Understanding these interactions is essential for effective watershed management and conservation. Detailed and localized research is crucial for uncovering the processes that shape water flow, erosion, and sediment transport within the watershed. Insights gained from such studies enable the development of targeted management strategies to address water resource challenges, mitigate erosion, and preserve ecological balance, ensuring sustainable development and environmental health.

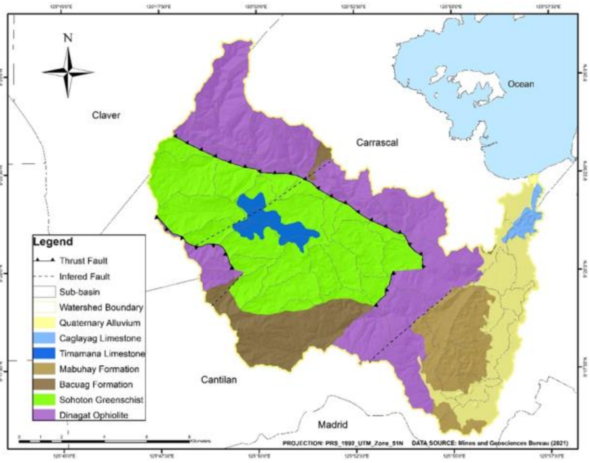

Fig. 2. Geologic map of the study area from the Mines and Geosciences Bureau (MGB) [2].

The Late Cretaceous Dinagat Ophiolite is the dominant geological formation in the watershed, consisting of serpentinized ultramafics, which are densely fractured or jointed in the east, and some portions in the west (Fig. 2). The Sohoton Greenschist, composed of phyllite and low-grade metamorphic sedimentary and volcanic rocks is in thrust fault contact with the basement Dinagat Ophiolite (Figs. 2 & 3). Sedimentary formations, Bacuag and Mabuhay Formations, unconformably overlie the basement units. The Miocene Timamana Limestone overlies the Sohoton Greenschist in the western portion of the watershed, while the Quaternary Caglayag Limestone capped the watershed in the east.

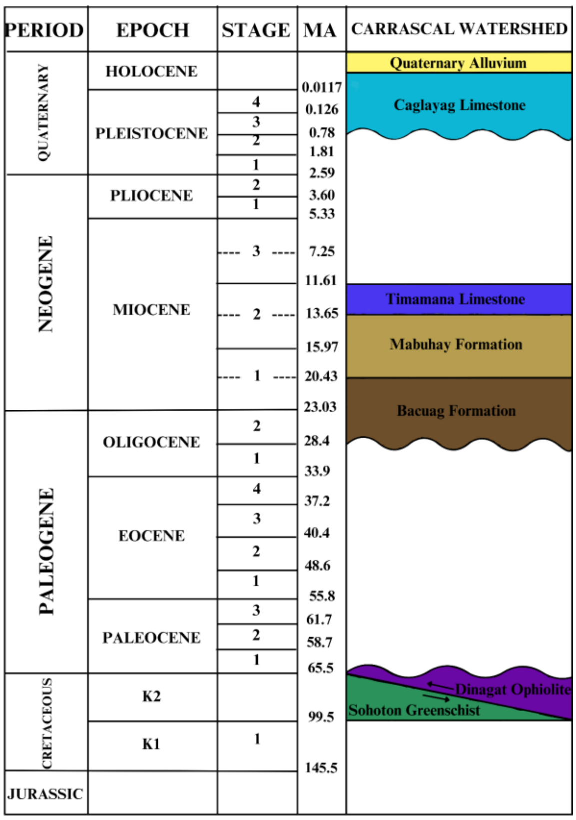

Fig. 3. Stratigraphic column in Carrascal watershed [2].

In terms of structures, aside from the prominent NW-SE trending thrust fault between the ophiolite unit and the metamorphic basement, several inferred faults were also identified (Fig. 2). These inferred faults are found in the northern portion cutting across the Sohoton Greenschist, Timamana Limestone, and Dinagat Ophiolite. Another fault transects the boundary of Dinagat Ophiolite and Mabuhay Formation in the east.

Advancements in remote sensing and geographic information systems (GIS) have bolstered lineament mapping and stream morphometry analysis, allowing rapid assessment of vast and remote areas with unprecedented detail. These technological innovations have significantly enhanced watershed management practices, enabling comprehensive studies integrating lithological data, geological structures, and morphometric parameters [1].

Despite these advancements, most of the watershed studies conducted in Mindanao Island are concentrated in the large basins such as the Agusan River Basin [3] and [4]. Certain watersheds, such as the Carrascal watershed in Surigao del Sur, Philippines, remain under-researched in terms of hydro-morphometry. This knowledge gap hinders a thorough understanding of the watershed's hydrological behavior, complicating efforts in conservation planning and disaster risk reduction.

2. MATERIALS AND METHODS

Drainage delineation, boundary of the sub-basins and lineament extraction were created from the IFSAR DEM with a 5m resolution using ArcMap 10.8 toolbox. The lineaments were extracted using 8 azimuths (0°, 45°, and 90°, 135°, 180°, 225°, 270°, 316°) which were adapted from the method of Das [5]. The existing geologic map from MGB was also digitized in ArcMap 10.8. The basic morphometric parameters, such as basin area, perimeter, and relief, of each sub-basin were calculated using ArcMap 10.8, and the rest of the parameters were calculated using formulas consolidated by Strahler [6]. Morphometric parameters under the linear aspect include basin length (L), stream order (U), and bifurcation ratio (Rb). Parameters under the area aspect include form factor (Ff), elongation ratio (Re), circularity ratio (Rc), shape factor (Bs), compactness coefficient (Cc), drainage density (Dd), stream frequency (Fs), drainage texture (T), and constant of channel maintenance (C). Parameters under the relief aspect include basin relief (R), relief ratio (Rr), and ruggedness number (Rn). The drainage morphometric parameters utilized in the study were determined and defined by [6], [7] and [8] .

The morphometric parameters were all subjected to principal component analysis using IBM SPSS to reduce the 18 parameters into a smaller number of parameters that hold most of the variability of the whole parameter. These remaining parameters were further subjected to correlation analysis using Pearson's r [9] correlating the spatial data [3]. These were correlated with the area of each lithology within a sub-basin and geologic structures, specifically the total lengths of lineaments within a sub-basin. This was done in order to determine which parameters are controlled by geology. Field validation was done after the thematic maps were consolidated, especially the verification of the lithologic and lineament data.

3. RESULTS AND DISCUSSION

3.1 Lineament Extraction and Validation

Accessible outcrops with delineated lineaments were thoroughly validated (Fig. 4). These outcrops (Fig. 4b and 4c) which are primarily underlain by ultramafic rocks from the Dinagat Ophiolite, exhibiting joint sets oriented at N30°E and N35°W. These orientations closely align with the trend of the neighboring river network, striking NW. The similarity in the orientation of the joints on the outcrop was instrumental in validating the identified lineaments. The orientation of these geological structures, such as joints and lineaments, provides valuable insights into the direction of the stream. The mapped thrust fault contact between the Dinagat Ophiolite and the Sohoton Greenschist further substantiates the significant influence of geology on the river network. The proximity to the fault contact indicates that tectonic activities and geological formations play a crucial role in shaping the drainage patterns.

The structural control of the drainage network is further supported by the presence of joints and lineaments that guide the flow of water. These features create zones of weakness in the rock, which water exploits to form channels and streams. As a result, the river network's direction and alignment can be largely explained by the underlying geological structures.

3.2 Principal Component Analysis

The Principal Component Analysis (PCA) process generated a set of eigenvalues, which are crucial for understanding the variance explained by each principal component (Table 1). Eigenvalues in PCA are fundamental metrics that quantify how much of the total variability in the dataset is captured by each principal component. They offer insights into the importance and relevance of each component within the analysis. In PCA, an eigenvalue represents the amount of variance associated with a corresponding principal component. Typically, components with eigenvalues greater than or equal to 1 are deemed significant because they account for a substantial proportion of the total variability in the dataset. This criterion is based on the Kaiser criterion, which suggests retaining components with eigenvalues of 1 or more, as they are likely to be informative and contribute meaningfully to the data's structure [10].

For the dataset analyzed in this context, the eigenvalues for components 1 through 5 are all greater than or equal to 1. This observation indicates that these components capture a significant portion of the variability present in the dataset. As a result, components 1 to 5 are considered essential for the analysis, as they collectively encompass the majority of the variance and, therefore, provide a robust representation of the underlying patterns and structures within the data.

Table 1. Total variance explained.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% Variance	Cumulative %	Total	% of Variance	Cumulative %
1	6.164	34.244	34.244	6.164	34.244	34.244
2	4.496	24.975	59.219	4.498	24.975	59.219
3	1.860	10.335	69.554	1.860	10.335	69.554
4	1.468	8.156	77.71	1.468	8.156	77.710
5	1.024	5.689	83.399	1.024	5.689	83.399
6	0.966	5.366	88.765			
7	0.713	3.960	92.724			
8	0.602	3.346	96.071			
9	0.415	2.307	98.378			
10	0.124	0.690	99.068			
11	0.055	0.305	99.372			
12	0.050	0.276	99.648			
13	0.025	0.141	99.789			
14	0.018	0.102	99.891			
15	0.011	0.064	99.955			
16	0.004	0.025	99.980			
17	0.002	0.014	99.993			
18	0.001	0.007	100.00			

By focusing on these significant components, dimensionality of the dataset will be efficiently reduced while retaining the critical information. This approach allows for a more streamlined and interpretable analysis, highlighting the most influential aspects of the data and facilitating deeper insights into its inherent relationships and trends.

The rotated component matrix offers a comprehensive view of the correlation between the 18 parameters and the five principal components identified through PCA (Table 2). This matrix facilitates a clearer

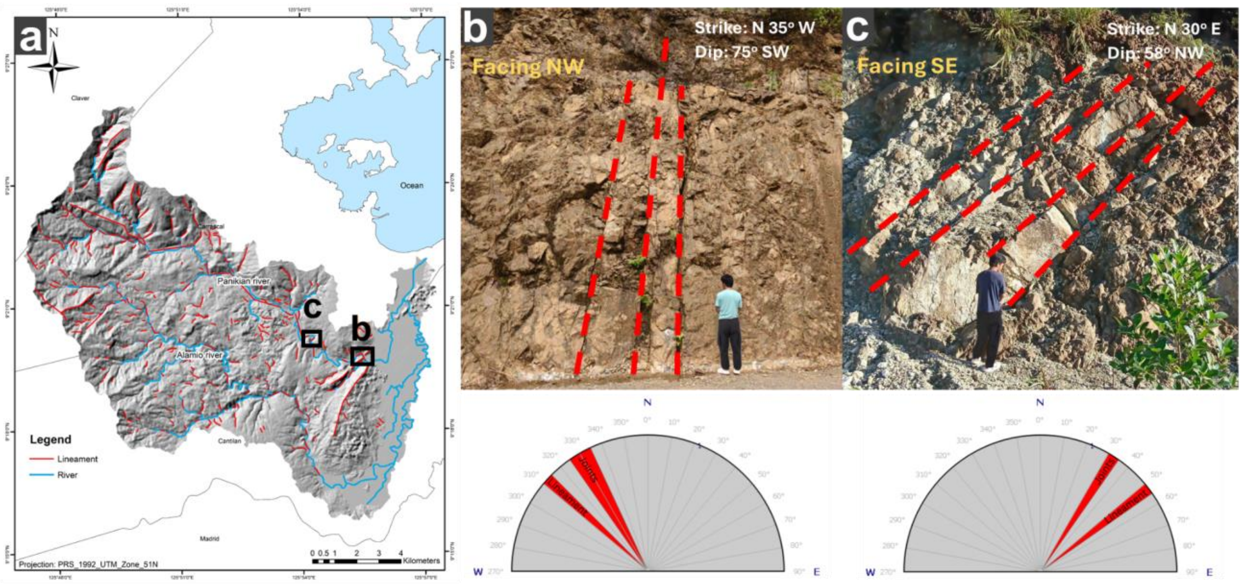

Fig. 4. Lineament map of Carrascal watershed (a) and field validated lineaments and joint structures (b and c) with their corresponding strike directions projected on the rose diagrams.

understanding of which parameters are most strongly linked to each component, aiding in the interpretation of the data. For component 1, basin length shows the highest loading at 0.960, making it the most significant variable for this component. This high loading indicates that variations in basin length are closely associated with the overall variability captured by component 1.

For component 2, the parameter with the highest loading value is basin relief, which is 0.936. This high loading indicates that basin relief is the most influential parameter in defining component 2. This suggests that variations in basin relief are a major factor in the patterns identified by component 2. Similarly, component 3 is predominantly represented by the circularity ratio, which has the highest loading within this component. This high loading signifies the circularity ratio's importance in shaping the definition of component 3.

For component 4, the parameter with the greatest loading is drainage texture. The high loading of drainage texture in this component reflects its significant contribution to the analysis of drainage characteristics, emphasizing its role in understanding the spatial arrangement and density of the drainage network.

Table 2. Rotated Component Matrix

Parameters	Component				
	1	2	3	4	5
Basin length	0.960				
Shape factor	0.950				
Elongation ratio	-0.939				
Sum stream length	0.918				
Sum stream number	0.914				
Form factor	-0.897				
Basin relief		0.938			
Relief ratio		0.936			
Ruggedness number		0.925			
Drainage density		-0.566	-0.509	0.470	
Constant of channel maintenance		0.557	0.476	-0.480	
Bifurcation ratio		-0.429			
Circularity ratio			0.890		
Compactness coefficient			-0.885		
Drainage texture				0.934	
Stream frequency				0.918	
Bifurcation ratio III/IV					0.646
Bifurcation ratio IV/V					0.590

3.3 Correlation Analysis

Correlation analysis and their significant correlations at $p < 0.01$ and $p < 0.05$ (highlighted in red) are summarized in Tables 3 and 4. The parameter basin length (L) significantly correlated with the total lineament length. This correlation suggests that increasing the total lineament length can increase the basin's length. Basin relief is the difference between the highest and lowest elevations in the watershed. It presents the steepness of slopes and terrain, which dictates erosional processes especially in landslide prone areas. The significant correlation of the parameter basin relief (R) to the total lineament length can indicate that the total lineament length of the structures contributes to the elevation difference between the highest point (1162 m) and the outlet point (5 m) in the watershed (Fig. 5). The Dinagat Ophiolite has generally higher elevated terrain in the watershed than other geologic formations. The boundary between Dinagat Ophiolite and Sohoton Greenschist is a thrust fault, which is already identified as a lineament (Fig. 4), where thrust fault contact is noted between these units. This explains the significant correlation between the total lineament length and the basin relief.

Table 3. Correlation table of total lineament length and the five components

		Basin length (L)	Basin relief (R)	Circularity ratio (Rc)	Drainage texture (T)	Bifurcation ratio (Rb) III/IV
Total lineament Length	Pearson Correlation	0.606	0.375	0.204	-0.212	0.452
	Sig. (2-tailed)	0.00	0.009	0.163	0.148	0.001
	N	49	49	49	49	49

Table 4. Correlation table of lithology and the five components

		Basin length (L)	Basin relief (R)	Circularity ratio (Rc)	Drainage texture (T)	Bifurcation ratio (Rb) III/IV
Timamana Limestone	Pearson Correlation	0.171	0.022	0.134	0.006	-0.053
	Sig. (2-tailed)	0.239	0.882	0.359	0.965	0.716
	N	49	49	49	49	49
Mabuhay Formation	Pearson Correlation	0.332	-0.215	-0.114	0.311	0.292
	Sig. (2-tailed)	0.020	0.138	0.435	0.030	0.042
	N	49	49	49	49	49
Bacuag Formation	Pearson Correlation	0.176	0.145	0.024	-0.118	-0.093
	Sig. (2-tailed)	0.241	0.337	0.872	0.434	0.538
	N	49	49	49	49	49
Sohoton Greenschist	Pearson Correlation	0.378	0.277	0.248	-0.219	-0.001
	Sig. (2-tailed)	0.007	0.054	0.085	0.130	0.994
	N	49	49	49	49	49
Dinagat Ophiolite	Pearson Correlation	0.466	0.231	0.082	0.010	0.652
	Sig. (2-tailed)	0.001	0.122	0.586	0.949	0.00
	N	49	49	49	49	49

The significant correlations between basin length and three geologic formations—namely, the Mabuhay Formation, Sohoton Greenschist, and Dinagat Ophiolite (Table 4)—indicate that geological factors can influence the length of the basins in the Carrascal watershed. This indicates that the varying rock types, such as clastic sedimentary rocks (Mabuhay Formation), metamorphic rocks (Sohoton Greenschist), and ultramafic and mafic rocks (Dinagat Ophiolite), play a crucial role in determining the length of the sub-basins.

The different lithologies present within these formations contribute to the overall geomorphological characteristics of the watershed. Clastic sedimentary rocks, typically found in the Mabuhay Formation, have distinct physical properties compared to metamorphic rocks like those in the Sohoton Greenschist and ultramafic and mafic rocks in the Dinagat Ophiolite. One notable aspect is the susceptibility of ultramafic and mafic igneous and metamorphic rocks to fracturing. These types of rocks are generally more prone to developing fractures compared to sedimentary rocks. This increased susceptibility to fracturing likely leads to more pervasive lineaments within the Dinagat Ophiolite and Sohoton Greenschist (Fig. 6). Another factor is the generally older age of Dinagat Ophiolite and Sohoton Greenschist compared to the younger sedimentary formations, which renders these units more susceptible to fracturing. These lineaments, indicating structural weaknesses, influence drainage patterns and basin lengths. Fractures and lineaments create longer drainage pathways as water flows along these zones of weakness, extending the basin lengths.

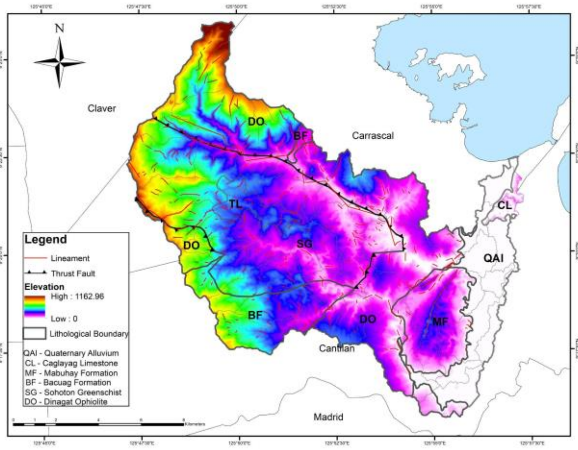

Fig. 5. Elevation map of Carrascal watershed.

The value of Rb is highly stable and shows a small range of variation from region to region or environment to environment, except where powerful geologic controls dominate [6], a value of less than five can indicate that the drainage basin is underlain by rocks of uniform resistance or no geological influence [11]. In the Carrascal watershed, there are 49 subbasins (Fig. 6), with sub-basins 11, 27, and 42- having an average bifurcation ratio greater than 25 and are also situated in Dinagat Ophiolite, Mabuhay Formation, and Sohoton Greenschist (Fig. 6b). Before PCA and correlation analysis were applied, morphometric analysis of the bifurcation ratio showed higher Rb values in the sub-basins of 11, 27, and 42. These were associated with dominant structural disturbance characteristics that changed the drainage pattern [6]. This leads to changing the drainage direction of the river from south-east to north-east (Figs. 1 & 6)

After applying PCA, the bifurcation ratio of stream order III/IV emerged as one of the five significant components. The statistical analysis revealed a notable correlation between this bifurcation ratio and the total lineament length, Dinagat Ophiolite, and Mabuhay Formation (Table 4). In the study area, sub-basins 6, 9, 10, 11, 27, 40, 41, 42, 43, and 49 exhibited bifurcation ratio (Rb) values greater than 5. These sub-basins are predominantly located within the Mabuhay Formation and Dinagat Ophiolite (Fig. 6a). This correlation indicates that the rock type and lineament structure within these formations significantly influence the characteristics of the sub-basins.

The Late Cretaceous Dinagat Ophiolite constitutes a portion of the watershed's basement unit, which is overlain by the Early to Middle Miocene Mabuhay Formation (Fig. 3). This geological configuration suggests that the geological control over the watershed was active from the Late Cretaceous until the Middle Miocene. Beyond this period, the geological influence appears to have diminished, indicating a shift in the factors affecting the watershed dynamics.

The significant influence of the rock types and lineament structures from the Dinagat Ophiolite and Mabuhay Formation underscores the importance of geological factors in shaping the watershed's hydrological and geomorphological characteristics during this period. However, from the Middle Miocene to the present, other factors likely became more dominant in influencing the watershed's behavior. These factors could include climatic changes, surface processes, and human activities, which may have played a more significant role in the more recent geological past.

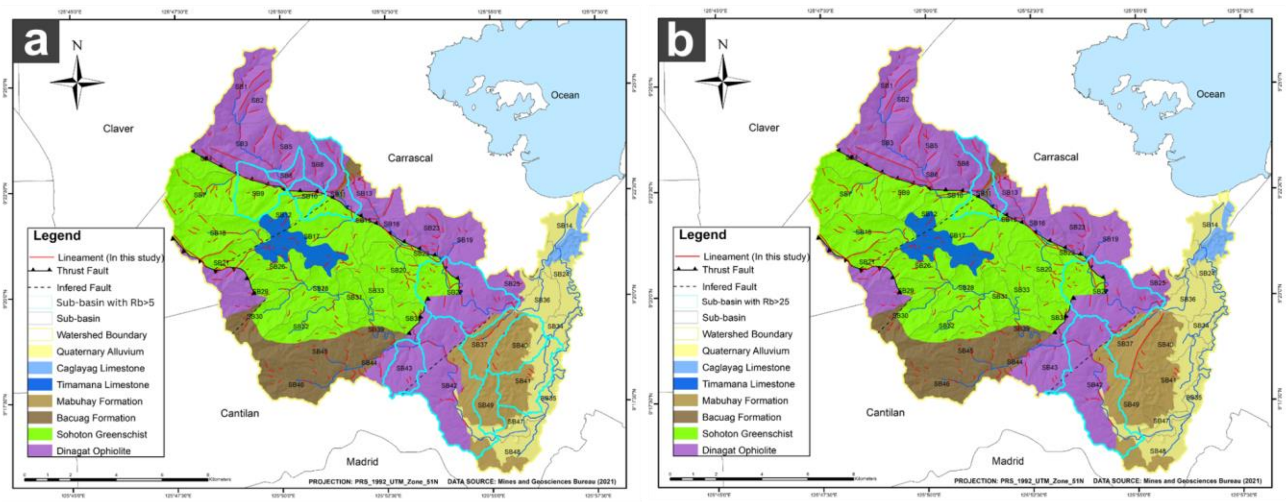

Fig. 6. Geologic base map with sub-basins highlighting Bifurcation ratio > 5 (Fig. 6a) and Bifurcation ratio >25 (Fig. 6b)

Drainage texture is a measure of the channel spacing within a watershed and is influenced by various factors, including the underlying lithology, infiltration capacity, and the relief of the terrain [9]. This parameter is categorized into five different textures: very coarse (< 2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8), and very fine (> 8) [1].

A fine drainage texture typically indicates the presence of soft or weak rocks, while a coarse drainage texture is associated with massive and resistant rocks. In the Carrascal watershed, it was found that only the Mabuhay Formation showed a significant correlation with drainage texture (Table 4). All sub-basins within the Mabuhay Formation are classified as having a fine texture, with values exceeding 8, based on the morphometric calculations. This suggests that the lithological composition of the Mabuhay Formation, which includes limestone, sandstone, and mudstone, contributes to the fine texture observed in the drainage channels. Such fine textures are indicative of a highly dissected landscape, characterized by significant surface runoff. This implies that the drainage network within the Mabuhay Formation is densely packed with channels, resulting from the relatively low resistance of its constituent rocks to erosion and weathering processes. The high degree of dissection and surface runoff in these areas further underscores the influence of lithology on the geomorphological features of the watershed.

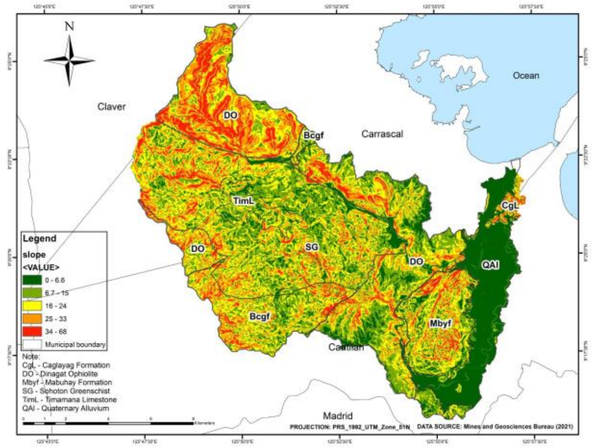

Fig. 7. Slope map of Carrascal Watershed

It is noticeable that in the correlation between lithology and bifurcation ratio, only two lithological formations are positively correlated- the Mabuhay Formation and Dinagat Ophiolite. According to Walia [12], a watershed can be influenced by many factors including anthropogenic activities, climate, vegetation, soil, geology, and slope. Examining the slope map of the Carrascal watershed (Fig. 7) reveals an interesting pattern in the distribution of lithological formations. Specifically, the formations that show no significant correlation with the bifurcation ratio (Table 4) are predominantly found in areas characterized by gentler slopes. This observation suggests that the slope of the terrain has a greater impact on the sub-basins, particularly those within the Sohoton Greenschist and Bacuag Formation, than the lithological characteristics themselves. Consequently, it can be inferred that gentle slopes exert a more substantial influence on these sub-basins' geomorphological and hydrological behavior than the underlying lithology. This highlights the importance of considering topographical features when studying watershed characteristics and their implications for environmental and geological processes.

3.4 Tectonic Reconstruction

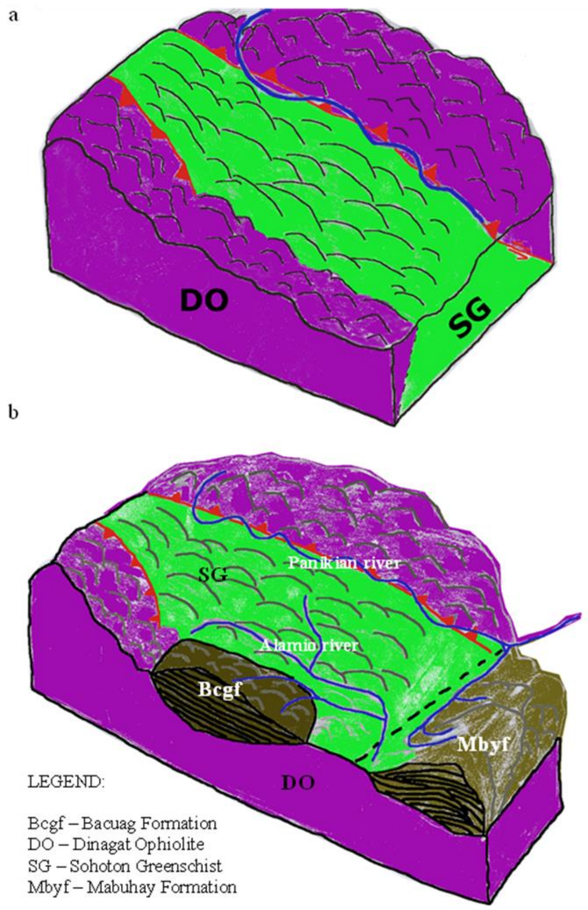

Fig. 8. Basin evolution of the Carrascal watershed during (a) the Late Cretaceous period and (b) the Middle Miocene epoch.

The Late Cretaceous Dinagat Ophiolite was thrusted above the Sohoton Greenschist (Fig. 8a), a region where the Panikian River is located. Interpreting the statistical findings, it becomes evident that geologic activities began significantly influencing the Carrascal watershed during the Late Cretaceous Period. The correlation between the bifurcation ratio and lithology reveals that only the Dinagat Ophiolite and the Middle Miocene Mabuhay Formation exhibit a significant correlation. This indicates that the influence of geology on the watershed is confined to the periods of Late Cretaceous to the Middle Miocene. Notably, the Sohoton Greenschist and Bacuag Formation, which are older than the Middle Miocene Mabuhay Formation, show no significant influence on the watershed. This lack of influence can be attributed to the gentle topography that characterizes these formations. Gentle slopes can result from various factors, making it challenging to determine the precise role of lithology in the drainage network. Additionally, the younger limestone formations also do not significantly impact the watershed, likely due to their relatively recent geomorphological development. Karst terrains, in particular, possess a complex set of geomorphic factors that influence their hydrology. The interpretation of the geologic history of the

4. CONCLUSIONS AND RECOMMENDATIONS

The impact of lithology and lineament structures on the drainage morphometry of the Carrascal watershed reveals significant insights into how geological features shape watershed characteristics. The integration of PCA and correlation analysis with morphometric parameters has provided a comprehensive understanding of the interplay between geological factors and drainage patterns.

The correlation between total lineament length and basin length highlights the critical role of geological structures in determining the spatial extent of drainage networks. Increased lineament length tends to elongate basin length, underscoring the influence of structural features on hydrological pathways. The significant correlation between total lineament length and basin relief emphasizes the impact of geological structures, particularly the Dinagat Ophiolite and Sohoton Greenschist, on the topographic variation within the watershed. This finding points to how tectonic activity and geological formations contribute to the elevation differences observed in the watershed.

A notable correlation between the bifurcation ratio and geological formations such as the Dinagat Ophiolite and Mabuhay Formation were observed. This relationship suggests that geological formations significantly influence drainage network characteristics, including the branching patterns of streams. Geological influence on the watershed's morphometry has evolved over time. The Late Cretaceous Dinagat Ophiolite and the Middle Miocene Mabuhay Formation have had a more pronounced impact compared to older and younger formations.

Understanding the geological influences on drainage patterns can aid in better watershed management and conservation efforts. The findings can help identify areas prone to erosion or landslides, facilitating targeted risk assessments and management strategies.

To gain a more detailed understanding of the geological history and drainage network evolution, incorporating qualitative studies such as field surveys, paleontological, geophysical, and geochemical analyses is recommended. These methods could provide deeper insights into the historical and ongoing geological processes affecting the watershed. The results are valuable for government agencies like the Department of Environment and Natural Resources (DENR) in the Philippines. Integrating geological and lineament analyses into watershed characterization can improve resource management, environmental conservation, and hazard risk assessment.

5. ACKNOWLEDGEMENT

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