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Geomorphometric Characterization and Analysis of the Bued Watershed Using Advanced Spaceborne Thermal Emission and Reflection Radiometer – Global Digital Elevation Model V3 through Geospatial Techniques

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The present study analyzed and quantified the linear, areal, and relief geomorphometric aspects of the Bued Watershed in Benguet, Philippines using a 30-m spatial resolution digital elevation model. The study was carried out using geospatial techniques to describe the hydrogeological processes acting on the watershed including its landforms, geologic structure, and terrain features that are relevant in watershed conservation and natural resources management. The study site has a total area of 146.46 km² and a basin length of 23.38 km. Based on the linear parameters, it has four stream orders generated using a 1.5-ha critical source area (CSA). Stream order three, with a total of three stream segments, contributes much higher sediment loads to the Bued River. These stream segments are also controlled by geologic structures with a high possibility of flash floods during a high rainfall intensity. For the areal parameters, the study area was categorized as medium-watershed and less elongated. It has a low drainage density value (1.16 km/km²), which is characterized by a good vegetative cover. The study site has permeable subsurface material and lower relief, which turns out to have a more infiltration capacity. Whereas the drainage texture and form factor values (0.812 km and 0.27, respectively) described the study area with a lower peak flow of longer duration, these values indicate that the flood flows are easier to control. The linear parameters showed that most of the Bued Watershed area (44%) is located at an elevation of > 1000 masl with moderate to steep slopes, which make it more susceptible to erosions and landslides. This is consistent with the relief ratio and relative relief results (0.08 and 0.03, respectively), which suggest that the area is vulnerable to erosion.

Keywords: ASTER, digital elevation model, geospatial analysis, geomorphometry, QGIS, watershed

INTRODUCTION

Geomorphometry of a watershed is the quantitative characterization, measurement, and analysis of the geological structures and landforms of the basin (Clarke 1996). As emphasized by Horton (1932), geomorphometric analysis plays a fundamental role in understanding the hydro-geologic processes and landform structures of a watershed. Thus, the watershed-based geomorphometric analysis has relevant contributions in any hydrological studies and management interventions such as identification of groundwater potential, runoff characteristics, stream volume management, watershed characterization, and vulnerability assessment to landslides, flooding, and

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erosions. In the quantitative measurement and analysis of the geomorphometric parameters, three aspects are considered to derive the general characteristic of the watershed: the linear, areal, and relief aspects (Melton 1958; Strahler 1964). Through these aspects, including the ground slopes, the geomorphology characteristics of a watershed and its stream network and tributary arrangements can be well-understood.

Various geomorphometric parameters can be determined and analyzed in any watershed (Miller 1953); however, the parameters used in this study were selected in consideration with the Technical Bulletin (TB) 16-A Series of 2019 or the "Revised Supplemental Guidelines and Procedures of Watershed Characterization and Climate Resilient Vulnerability Assessment of Watersheds and Preparation of Integrated Watershed Management Plan" (IWMP) issued by the Forest Management Bureau (FMB) – Department of Environment and Natural Resources (DENR). The purpose of selecting the parameters prescribed in the TB is to assist the DENR technical personnel and staff in the formulation and analysis of the watershed characterization reports in the Province of Benguet and other watersheds in the Cordillera Administrative Region (CAR) that can be duplicated in any watersheds in the Philippines as well. The linear aspect covers the stream order, stream length (per order and the total), bifurcation ratio, the average bifurcation ratio, basin length, and the length of overland flow. For the areal aspects, the watershed area, drainage density, circulatory ratio, elongation ratio, stream frequency, drainage texture, and form factor were considered, while elevation classes (minimum and maximum included), slope classes, relief ratio, and relative relief were considered for the relief aspect.

The general objective of the study is to characterize and analyze the linear, areal, and relief geomorphometric parameters of the Bued Watershed located in Benguet Province using high-resolution DEM through geospatial techniques. As carried out by several researchers, the use of DEM and Geographic Information System (GIS) techniques in the geomorphometric analysis of a watershed proved to be an efficient tool that provides science-based and statistically-sound results to characterize watersheds.

MATERIALS AND METHODS

Description of the Watershed Area

The Bued Watershed is located between latitude 16.411395° and longitude 120.616182° in the north and latitude 16.165628° and longitude 120.608177° in the south in the Province of Benguet. The headwaters came from Baguio City, while the Municipality of Tuba covers the majority of the watershed area. A small portion along the eastern side of the watershed is located in Itogon (Figure 1). Approximately, the watershed has an area of

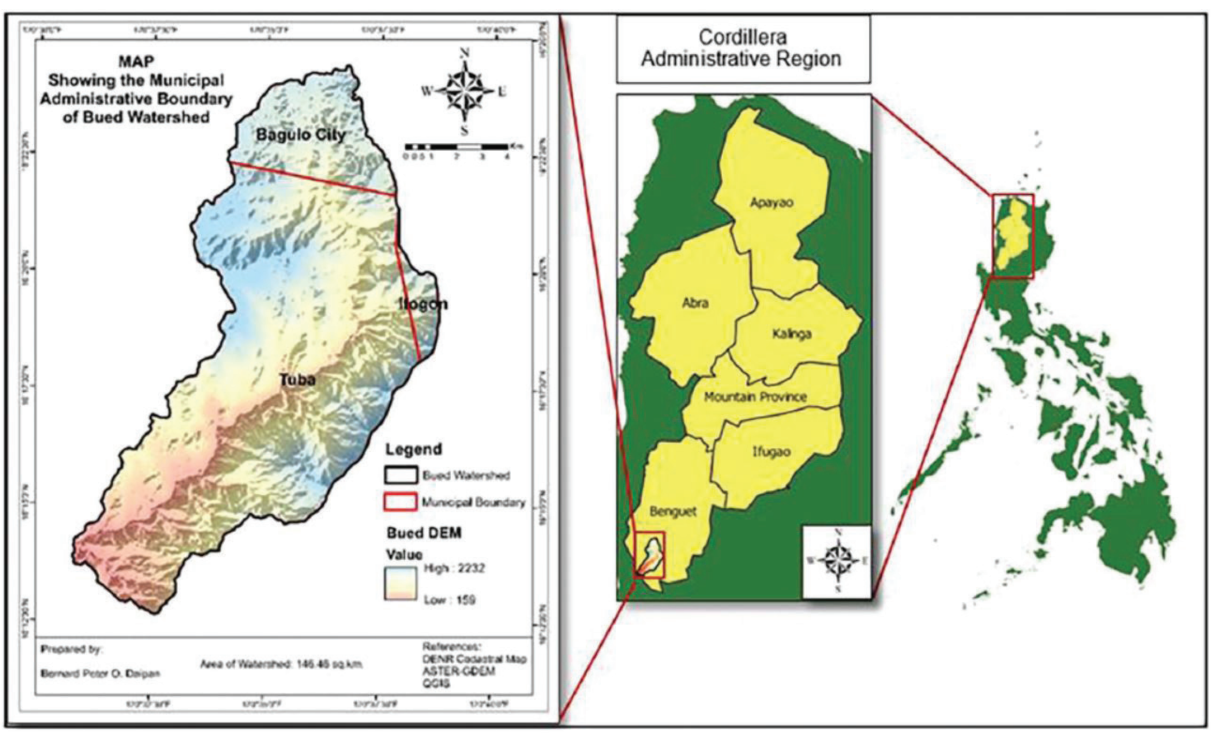

Figure 1. Bued Watershed boundary and location map of the study site.

146 km² and topographically lies between 159–2,232 m above sea level (masl). The major stream, or the Bued River, drains toward the boundary between the Municipality of Rosario in La Union and the Municipality of Sison in Pangasinan and merges with the Angalacan River in Mangaldan, Pangasinan to form the Cayanga River, which drains into the Lingayen Gulf between San Fabian and Dagupan City in Pangasinan. The watershed boundary used in the study was generated using the ASTER-DEM data.

Data

The primary data used to analyze the geomorphometric parameters of the Bued Watershed is the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3. ASTER is a Japanese remote sensory device aboard the satellite named Terra that was launched in 1999 through the National Aeronautics and Space Administration (NASA). The high-resolution (30 m) images and data produced by ASTER are used to generate comprehensive maps of reflectance and surface temperature of the land, as well as elevation models (NASA 2020). The version 3 of ASTER-GDEM was jointly released by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States through NASA in 2011. The data is available for download from Japan Space Systems and NASA Earthdata websites. The product is open-source or free of charge for any user/researcher pursuant to an agreement between NASA and METI.

Geospatial Analysis

The geospatial techniques and analysis of the geomorphometric parameters of the Bued Watershed were performed using the Quantum Geographic Information System (QGIS) Version 3.2.1 software. QGIS is free and open-source software for GIS operations and analysis, which is an official project of the Open Source Geospatial Foundation (OSGeo) that can create, edit, visualize, analyze, and publish geospatial information on Windows. The software can also be downloaded from the QGIS organization website.

After the acquisition or downloading of the ASTER-GDEM V3 (30 m x 30 m resolution) data covering the whole Bued Watershed, various geospatial techniques were conducted such as raster projections to re-project the raw map, as well as raster extractions to delineate and subset the watershed boundary, including the stream network generation. Terrain analysis hydrology was used to produce a Strahler order of stream channels, the calculations of stream length, basin length, relief ratio, relative relief, watershed area, drainage density, and stream frequency were performed using field calculator and statistical analysis tools from the software. The stream channels for the study site were generated through the r.stream.extract algorithm in Geographic Resources Analysis Support System (GRASS) QGIS.

Other parameters were determined without using geospatial techniques such as bifurcation ratio, circulatory ratio, elongation ratio, form factor, drainage texture, and length of overland flow. However, the input used to determine these parameters was dependent on other geomorphometric results using geospatial techniques. The equations used to derive the quantitative measurement of the geomorphometric parameters of the Bued Watershed are presented in Appendix I.

RESULTS AND DISCUSSION

Linear Parameters

Stream channels (S). Many previous studies on watershed geomorphometric analysis did not take into account the CSA in delineating stream channels. Other researchers, however, used the minimum threshold of drainage to be generated represented by raster cell spatial resolution. The CSA value is a great factor in the estimation of a stream channel, density, length, and orders. Without proper validation, it could lead to either overestimation or underestimation of stream parameters. To determine which CSA value is more appropriate in delineating the stream channels, three scenarios with different thresholds (1500, 1000, and 500) and CSA values (4.5 ha, 3 ha, and 1.5 ha) were executed in r.stream.extract algorithm in GRASS-QGIS (Figure 2). This algorithm has an option for the minimum flow accumulation for streams, represented by the number of cells, which can be used to delineate stream channels. Results showed that as the CSA value decreases, the number of stream channels and its length increases (Table 1). To determine which is the best CSA value to be used in the study, validation of the actual stream location was conducted through the digitization process in Google Earth Pro (Figure 2). Based on the validation output, the CSA with 1.5 ha value is considered to be more accurate (96%) compared to other CSA values; hence, it was used to generate the stream channels for the study site.

Stream order (U). Using Strahler's (1964) hierarchical ranking of stream segments, the highest level of U generated for the Bued Watershed is 4 (Figure 3). A total number of 103 stream segments from all Us were recorded (Table 2). The first U is considered as the fingertip stream. When the two 1st U stream segments meet together, the meeting point stream will form the 2nd U and so on; as the total number of stream segments decreases, the

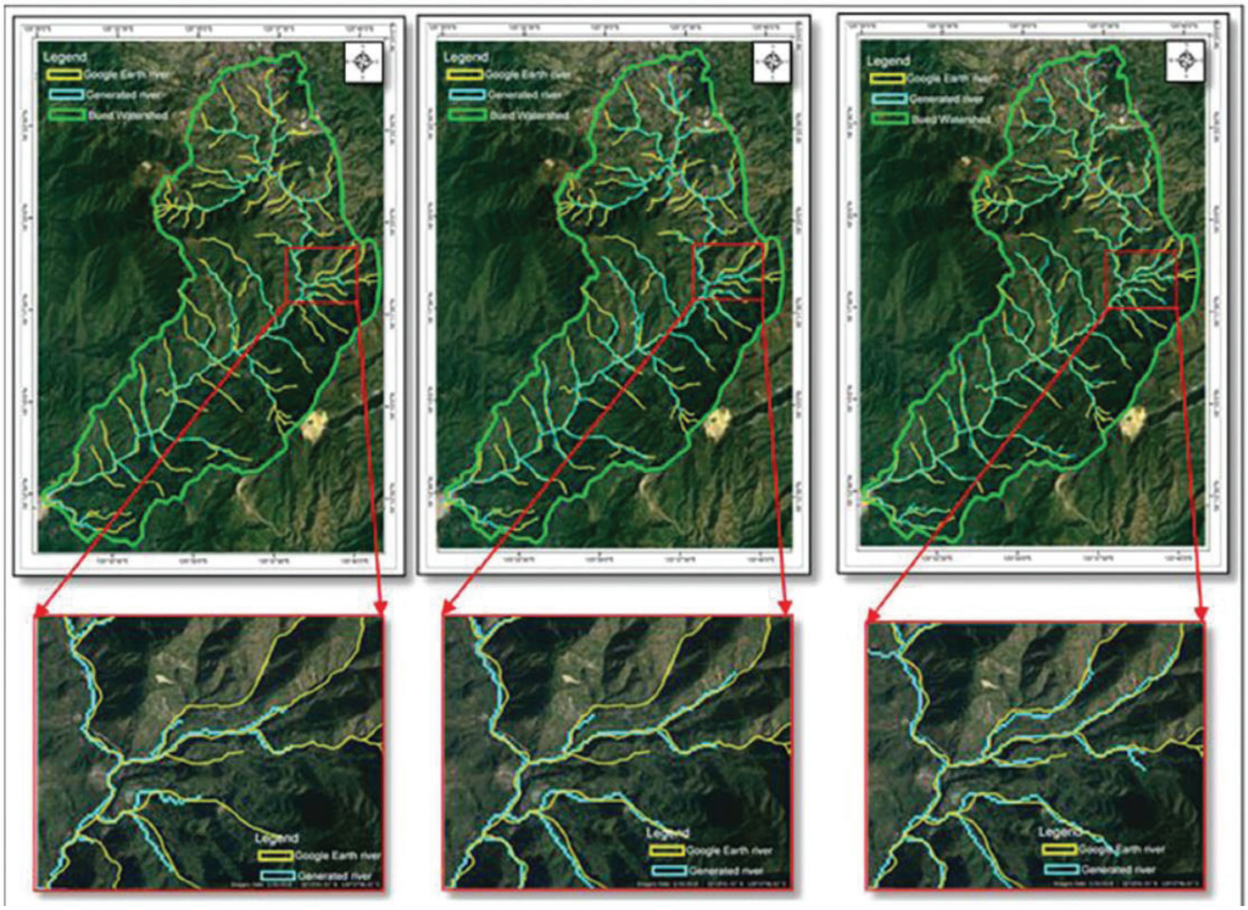

Figure 2. Validation of the generated stream channels in Google Earth Pro using different CSA values.

Table 1. Different scenarios to determine the suitable CSA value for stream channel delineation.

Scenarios	Minimum flow accumulation for streams (cells)	Critical source area (CSA) value (ha)	Number of stream channels	Total length of all streams (km)	Accuracy (based on the validation result using digitized stream channels in Google Earth)
1st	1500	4.5	39	77.95	44%
2nd	1000	3	58	100.31	57%
3rd	500	1.5	103	169.86	96%

Table 2. Stream order analysis.

Stream Order	Number of stream segments (Nu)	Stream length (Lu) (km)	Bifurcation ratio (Rb)
U1	79	92.97	
U2	20	42.83	3.95
U3	3	9.56	6.67
U4	1	24.50	3
Total	**103**	**169.86**	
Average			**4.54**

level of U increases. The highest U is usually the major stream of the watershed and is associated with greater water discharge and higher stream velocity. Based on the result, U3 will highly contribute to water discharge and increases the chance of erosion rates; the U3 streams with three segments will also contribute high sediment loads into the Bued River (Altaf *et al*. 2013).

Stream length (Lu). Results showed that Lu decreases as U increases, except for the major stream or the highest U (Table 2). As observed by Withanage and colleagues (2015), shorter Lu indicates steeper slopes while longer Lu

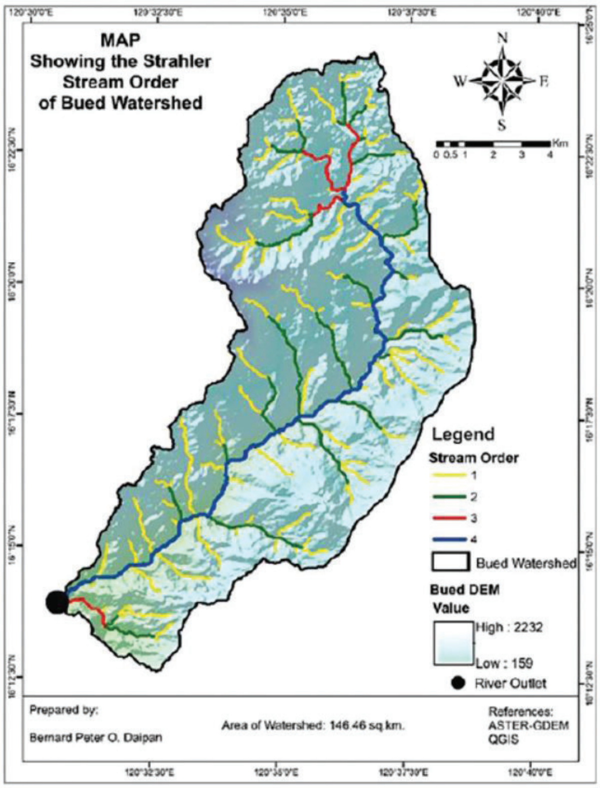

Figure 3. Stream order (U) of the Bued Watershed.

signifies relatively flat gradient; therefore, the portion of the Bued Watershed with the shortest Lu is more prone to erosion and landslide. The total Lu for the Bued Watershed is 169.86 km while the major stream has a length of 24.55 km. The Lu is also used to understand the surface flow discharge, which is very imperative in understanding the soil erosion rates in any watersheds (Kadam *et al*. 2016).

Bifurcation ratio (Rb). Rb is the ratio of the number of stream segments of a given stream order to the number of stream segments of the next higher order (Schumms 1956). The average Rb for the study site is 4.54, as the highest was recorded between U2 and U3 ratio with a value of 6.67 (Table 2). Low Rb values, within 3–5, indicates that the watershed is not affected by the geologic structures (Chow *et al.* 1988). On the other hand, higher Rb values mean that the watershed is controlled by geologic structures, which indicates a mature topography (Nag 1998). Further, higher Rb values indicate early hydrograph peak with a high possibility of flash floods during the rainy seasons or typhoon occurrences (Rakesh *et al*. 2001). Compared to the Rb of the Cagayan De Oro River Basin with a value of 1.8 (Talampas and Cabahug 2015), the Bued watershed has a higher possibility of flash floods because of its mature topography.

Basin length (Lb). The Lb is the measurements from the farthest drainage divide to the main outlet of the river basin following the principal flow path or the main channel (Horton 1945). The computed Lb of the Bued Watershed was 23.38 km. Lb is a very important input in the analysis and calculation of the relief ratio (Rh), elongation ratio (Re), and the form factor (Ff) of the watershed.

Length of overland flow (Lg). Horton (1945) described the Lg as the length of water flow in the ground before it becomes concentrated in definite stream channels. The computed Lg for the study area is 0.43 km; compared to other studies, the Lg for the Bued Watershed is relatively shorter. According to Altaf and colleagues (2013), shorter Lg values indicate steeper slopes which is more vulnerable to flash floods and erosions, while longer Lg values indicate gentle slopes in the watershed and less vulnerable to flooding since it takes longer time for the stream to swell.

Areal Parameters

Watershed area (A). The area of the watershed is usually measured in km². For the Bued Watershed, A is equal to 146.46 km² (Table 3). The present study area is categorized as a medium watershed (A = 100–500 km²) based on the watershed classification of DENR. Other categories include micro-watershed (A ≤ 10 km²), small watershed (A = 10–100 km²), large watershed (A = 500–1000 km²), and river basin (A ≥ 1000 km²). Bigger watershed areas have bigger rainfall catchment and more water volume during peak flows. Also, it has a longer time for stormwater to flow to the major stream outlet, thus preventing sudden flash floods (FMB 2019).

Drainage density (Dd). As defined by Horton (1945), Dd is the total length of stream order segments (TLu) (km) per A (km²) of the watershed. Dd is affected by the types of soil and water infiltration capacity of the watershed (Altaf *et al.* 2013), and it controls the travel time of water within the watershed (Dodov and Foufoula-Georgiou 2006). The Dd value for the Bued watershed was computed at 1.16 km/km², which has a lower value compared to the computed Dd for the Cagayan De Oro River Basin, which has a value of 2.29 km/km² (Talampas and Cabahug 2015). In general, Dd with a lower value (< 2.0 km/km²) is characterized by a good vegetative cover, permeable subsurface material, and lower relief, which turns out to have a more infiltration capacity (Luo 2000) as compared to higher Dd (2.5–3.0 km/km²) characterized by weak and impermeable sub-surface material with sparse vegetation and mountainous relief (Harlin and Wijeyawickrema 1985). The vegetation cover of the Bued Watershed was validated using the multi-temporal (2010 and 2015) land cover maps from NAMRIA (2020) geoportal, which shows that the study site has 44% forest cover in 2010 but was reduced to 39% in 2015. The shrubland or brush-land has a cover of 40% and 39% in 2010 and 2015, respectively

Table 3. Result of geomorphometric parameters analysis for the Bued Watershed.

Linear parameters	**Result**
Stream order (U)	Up to 4th level
Stream length (Lu)	169.86 km
Bifurcation ratio (Rb mean)	4.54
Basin length (Lb)	23.38 km
Length of overland flow (Lg)	0.43 km
Perimeter of the watershed (P)	68.62 km
Areal parameters	
Watershed area (A)	146.46 km²
Drainage density (Dd)	1.16 km/km²
Circulatory ratio (Rc)	0.39
Elongation ratio (Re)	0.59
Stream frequency (Fs)	0.7/km²
Drainage texture (Rt)	0.812 km
Form factor (Ff)	0.27
Relief parameters	
Elevation (masl)	
< 500	17.61 km²
500–1,000	46.94 km²
1,000–1,500	63.79 km²
1,500–2,000	17.45 km²
> 2,000	0.67 km²
Slope (%)	
0–8	20.33 km²
8–18	55.35 km²
18–30	54.56 km²
30–50	15.95 km²
> 50	0.26 km²
Relief ratio (Rh)	0.08
Relative relief (Rr)	0.03

(Figure 4). The Bued Watershed has a combined vegetative cover of 84% in 2010 and to 78% in 2015. Despite the decrease in forest and shrubland, the Bued Watershed – in general – has still a good vegetative cover compared to the forest cover and shrubland of the 14 subwatersheds (SWs) in the Muleta Watershed in Bukidnon and North Cotabato (Puno and Puno 2019).

Circulatory ratio (Rc). It is the ratio of the area of the watershed to the area of a circle having the same circumference as the perimeter of the watershed (Miller 1953). Rc has a significant impact on the hydrological response of the watersheds, such as the size and shape of flood peaks (Ward and Ronisons 2000). For the Bued Watershed, the computed Rc is 0.39. High Rc values (0.5–1) is a circular watershed that has a higher movement of runoff, whereas lower Rc values (< 0.5) have the least runoff frequency (Talukdar 2011).

Elongation ratio (Re). Re is the ratio of the diameter of a circle of the same area as the watershed to the basin length (Skristiyanti *et al.* 2018). The computed Re value for the Bued Watershed is 0.59. The Re value with 0.6–0.8 indicates a higher relief and steeper slope (Dar *et al.* 2013). On the other hand, a Re close to 1.0 is typically the watersheds with very low relief. Altaf and colleagues (2013) grouped the Re into three categories – namely, less elongated (< 0.7), oval (0.7–0.9), and circular (> 0.9). The Bued Watershed is a less elongated watershed, which means it has a slower hydrograph peak compared to circular watersheds that have quick hydrograph peaks (Potter and Faulkner 1987).

Stream frequency (Fs). It is the total number of stream segments of all orders per unit area of a watershed (Altaf *et al.* 2013). Fs values are related to infiltration capacity, permeability, and relief of watersheds (Montgomery and Dietrich 1989). Based on the analysis, the Fs for the Bued Watershed is 0.7/km², which is relatively lower compared to those in other studies. A high Fs value indicates early peak discharge that may result to flash flooding. A lower Fs value has low runoff rates that have a good vegetation cover and has high infiltration capacity (Patton and Baker 1976).

Drainage texture (Rt). Rt is used to evaluate the geometry and characteristics of the drainage network of the watershed, and it was categorized into five Rt classes: very coarse (Rt < 2 km), coarse (Rt = 2–4 km), moderate (Rt = 4–6 km), fine (Rt = 6–8 km), and very fine (Rt > 8 km) (Smith 1950). For the Bued Watershed, the Rt result falls under a very coarse texture with a value of 0.812 km. Rt is influenced by infiltration capacity; hence, a watershed with very coarse Rt has larger basin lag-time periods compared to other classes (Angillieri 2008). As discussed by Altaf and colleagues (2013), watersheds with low Rt value have a longer duration to peak flows, while higher Rt has a shorter duration. Further, a watershed with an Rt value of more than 8 is more susceptible to soil erosion (Skristiyanti 2018).

Form factor (Ff). Chandniha and Kansal (2014) defined Ff as the ratio of A to the square of the maximum Lb. They further emphasized that a higher Ff means the watershed is circular, while lower Ff means it is elongated in nature. The computed Ff value for the Bued Watershed is 0.27. Watersheds with high Ff values have high peak flows with a shorter duration, while elongated watersheds with low Ff values have lower peak flow of longer duration (Kochel 1988). Flood flows of elongated watersheds are easier to control and manage as compared to circular watersheds (Altaf *et al.* 2013).

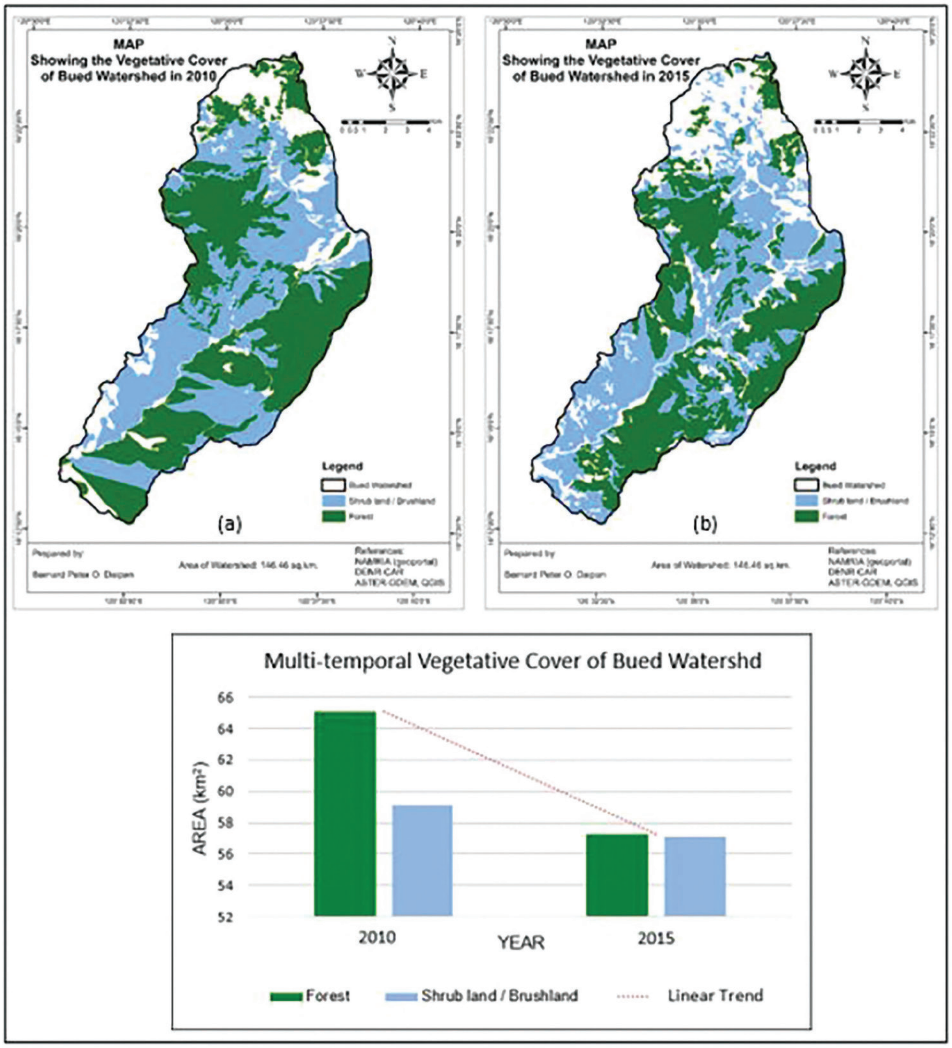

Figure 4. Multi-temporal vegetative cover of the Bued Watershed: (a) vegetative cover in 2010; (b) vegetative cover in 2015.

Relief Parameters

Elevation classes (masl). The elevation is the altitude above sea level or ground level. In this study, the elevation was derived from the ASTER-GDEM V3 covering the Bued Watershed downloaded from the website of NASA Earthdata with a 30-m cell spatial resolution. In the present study, the 500-m interval was used for the reclassification of elevation ranges from the lowest to the highest point (Figure 5). Results showed that most of the study area (44%) has an elevation between 1000–1500 masl, followed by 500–1000 masl with 32% of the study area. The above-2000 masl areas (0.45%) were also recorded in the watershed. Elevation will affect the type of vegetation in the watershed as well as the climate. As pointed out by Jin *et al.* (2008), the dominating factor for the vegetation growth and vertical distribution of various types of vegetative land cover is the elevation. Based on the vegetative land cover map produced by NAMRIA (2020), there are three forest types in the Bued Watershed: coniferous forest, broadleaved forest, and mixed forest. Using the geoprocessing techniques in QGIS, the area (km^2) of each forest type was computed across elevation classes (Figure 6). There are substantial differences in the vegetation/forest types through various elevations. As elevation increases, the broadleaved forest decreases. As for the coniferous forest, however, as the elevation reaches above 1500 masl, its clout started to decrease. For the mixed forest (coniferous and broadleaved), it is found in almost all the elevation classes except in areas above 2000 masl.

Slope classes (%). The slope data was generated using a percent rise in QGIS using the DEM of the study area (Figure 5). The classification of the slope was adapted from DENR-FMB (2019). Most of the areas in the Bued Watershed are represented by moderate to steep

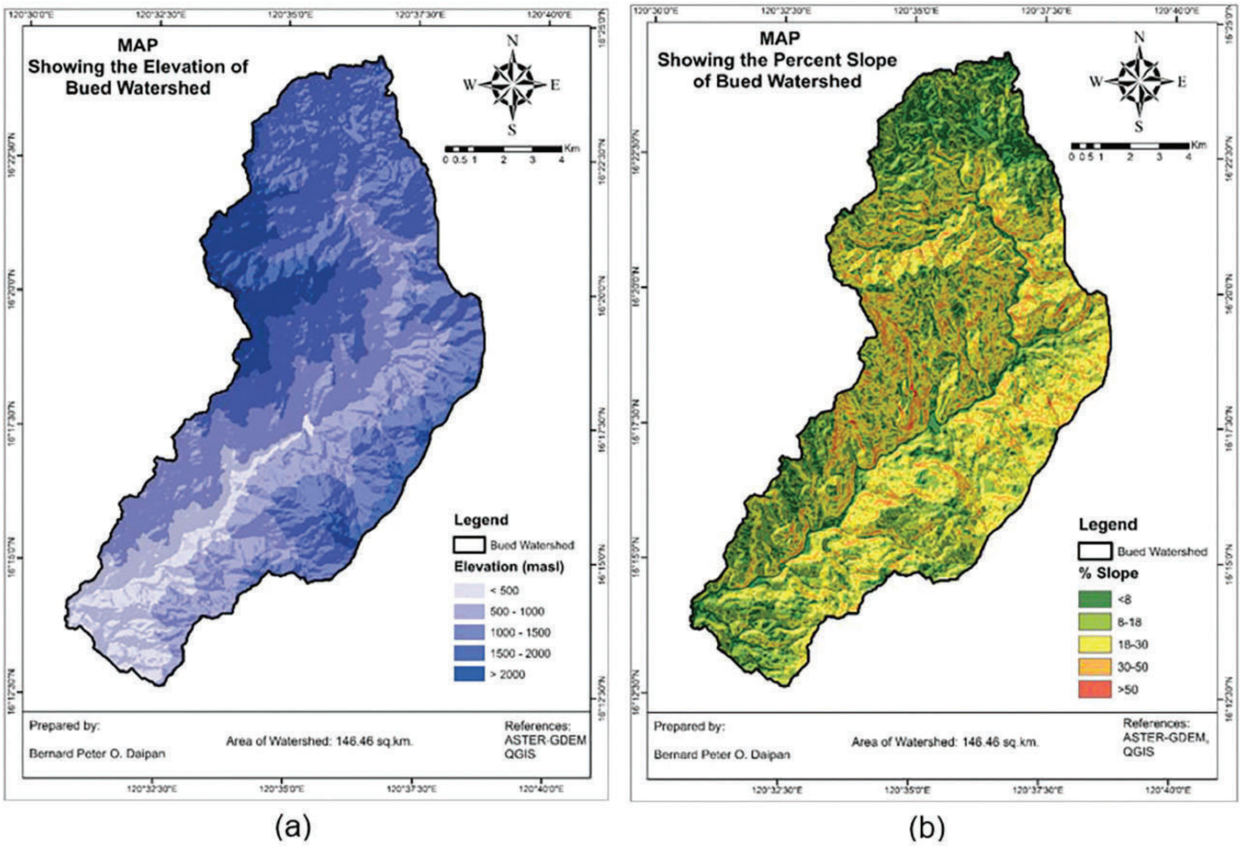

Figure 5. Relief parameters of the Bued Watershed: (a) elevation classes; (b) slope classes.

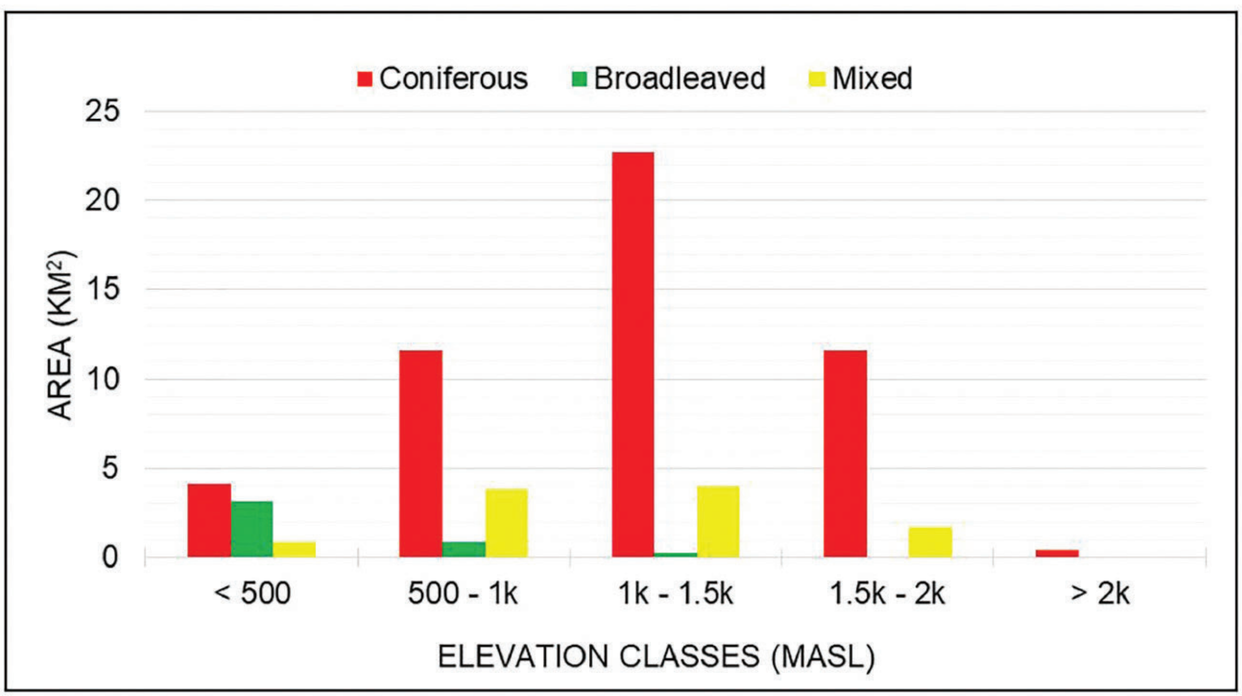

Figure 6. Forest types (NAMRIA 2020) at different elevation classes in the Bued Watershed.

slopes with 38% and 37% of the total area, respectively. Understanding the slope classification of the watershed area will give hints on the vulnerability of the watershed to various hazards such as landslides and erosions. In the present scenario, the majority of the Bued Watershed area is highly prone to landslides and erosions with 20 occurrences, as observed from the satellite imagery of Google Earth Pro (Appendix II).

Relief ratio (Rh). Schumms (1956) described that Rh is the ratio between the total relief (relative relief) of a watershed (elevation difference of lowest and highest points of a watershed in km) and the longest dimension of the watershed parallel to the major stream or the Lb. It is the measurement of the overall steepness of a watershed, which also manifests the severity of erosion and run-off occurrences (Dodov and Foufoula-Georgiou 2006). For the Bued Watershed, the Rh was calculated at 0.08; compared to those in the study of Asfaw and Workineh (2019), where they have computed Rh values of 0.026 and 0.027 for the two watershed study sites, the Rh for the Bued Watershed is way higher. Generally, the Rh values increase with decreasing area and size of the watershed (Gottschalk 1964). Studies suggest that watersheds with higher Rh values are more susceptible to erosions (Altaf *et al.* 2013). Based on the similar study conducted in the SWs of the Muleta Watershed in Bukidnon and North Cotabato in Mindanao, the Rh values for the three SWs with high conservation priority (SW 4, SW 13, and SW 14) were computed as 0.02, 0.04, and 0.03, respectively (Puno and Puno 2019). In comparison, the Bued Watershed has a higher Rh value than the three priority SWs, which indicates that the former is steeper in slope and more prone to landslides and erosion.

Relative relief (Rr). The Rr of the watershed is the actual variation in height, *i.e.* the difference between the maximum and minimum height (Sharma and Joshi 2018). The calculated Rr for the Bued Watershed is 0.03. Melton (1958), suggesting that Rr is the ratio of maximum basin relief. Higher Rr values mean higher Rh, which indicates the intensity of erosion going on across the slopes of the watershed (Chandniha and Kansal 2014).

CONCLUSION

The characterization and analysis of the various geomorphometric parameters of the Bued Watershed in Benguet, Philippines using geospatial techniques were carried out and were proven to be more effective than the conventional method. Using a high-resolution DEM for analysis has contributed to a more reliable and accurate result as observed through validation – particularly on the vegetative cover, stream channels, geologic structures, slopes, and existing landslides/erosion in the watershed. Based on the analyses and computation of the three major aspects – linear, areal, and relief aspects – the geomorphometric characteristics of the Bued Watershed were highly understood.

For the linear parameters, the present study found out that the Bued Watershed has four levels of Us using Strahler order. The U3 contributes much higher sediment loads to the Bued River. The Lu of U3 is more prone to erosions because it is shorter, which indicates that these streams have steeper slopes. In the same way, the Lg value of the Bued Watershed is relatively shorter, which indicates steeper slopes that make it more vulnerable to landslides and erosions. A high Rb value was recorded between U2 and U3, which means that it is controlled by geologic structures with a high possibility of flash floods during a high rainfall intensity. However, the mean Rb of the watershed has a lower value, which suggests that the Bued River has a lower probability of flash floods, except for extreme events like super typhoons and prolonged monsoon rains.

For the areal parameters, the Bued Watershed was categorized as a medium-watershed with a low Dd value (< 2.0 km/km^2), which is characterized by a good vegetative cover, permeable subsurface material, and lower relief that turns out to have a more infiltration capacity. The Rc and Re results suggest that the study area is not a circular watershed but a less elongated one (Re < 0.7) characterized by a higher relief and steeper slope with least runoff frequency and slower hydrograph peak, which is very consistent with the result of other parameters. On the other hand, the study area has a low Fs value, which means it has low runoff rates with a good vegetation cover and high infiltration capacity. Rt and Ff values described the study area, with a lower peak flow of longer duration where floodwater flows, are easier to control and manage compared to other watersheds.

The linear parameter analysis showed that the altitude for the majority of the Bued Watershed area is more than 1000 masl with moderate to steep slopes. The study area also recorded high Rh and Rr values, which make it more susceptible to landslides and erosions.

The results of this research may be of great help to the field implementing units of the DENR in the preparation and/or updating of the IWMP of the Bued Watershed, taking into consideration some appropriate management and conservation interventions to the different stream orders/channels. Moreover, the open-source software and geospatial techniques used in this study can be utilized and replicated by anyone in the field in conducting geomorphometric characterization of any watersheds in the country.

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NOTE ON APPENDICES

The complete appendices section of the study is accessible at http://philjournsci.dost.gov.ph

STATEMENT ON CONFLICT OF INTEREST

There are no known conflicts of interest associated with the publication.

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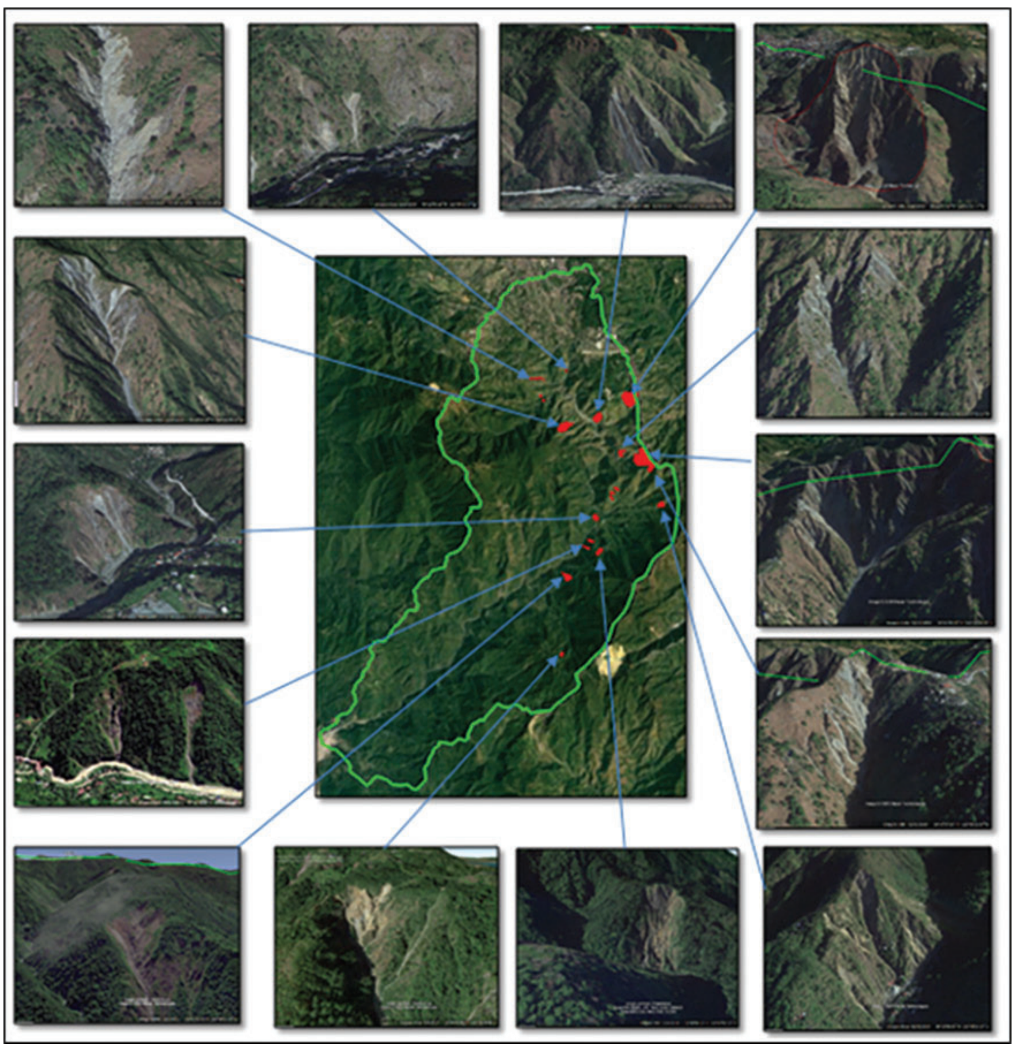
Appendix I. Equations used for the analysis of geomorphometric parameters.

Category	Geomorphometric parameters	Equation	Unit	Source
Linear aspect	Stream channel (*S*)	S delineation using CSA value $CSA = T \times R$ where: CSA = critical source area T = threshold for minimum flow accumulation R = raster cell spatial resolution	ha	GRASS QGIS
	Stream order (*U*)	Hierarchical rank	unitless	Strahler (1964)
	Stream length (*Lu*)	Generated from QGIS	km	Strahler (1964)
	Bifurcation ratio (*Rb*)	$Rb = \frac{Nu}{Nu+1}$ where: *Rb* = bifurcation ratio *Nu* = total no. of stream segments of order "u" *Nu + 1* = number of segments of the next higher order	unitless	Schumms (1956)
	Basin length (*Lb*)	Generated from QGIS	km	Horton (1945)
	Length of overland flow (*Lg*)	$Lg = \frac{1}{2Dd}$ where: *Lg* = length of overland flow *Dd* = drainage density	km	Horton (1945)
Areal aspect	Watershed area (A)	Generated from QGIS	km²	ASTER-GDEM
	Drainage density (*Dd*)	$Dd = \frac{TLu}{A}$ where: *Dd* = drainage density *TLu* = total stream length in km *A* = area of watershed in km²	km/km²	Horton (1932)
	Circulatory ratio (*Rc*)	$Rc = \frac{(4\pi A)}{P^2}$ where: *Rc* = circulatory ratio *π* = pi = 3.1416 *A* = area of watershed in km² *P* = perimeter of watershed in km	unitless	Miller (1953)
	Elongation ratio (*Re*)	$Re = \frac{2/Lb}{(A/\pi)^{0.5}}$ where: *Re* = elongation ratio *Lb* = basin length in km *A* = area of watershed in km² π = pi = 3.1416	unitless	Schumms (1956)
	Stream frequency (*Fs*)	$Fs = \frac{Nu}{A}$ where: *Fs* = stream frequency *A* = area of watershed *Nu* = total number of streams of all orders	per km²	Horton (1932)
	Drainage texture (*Rt*)	$Rt = Dd \times Fs$ where: *Rt* = drainage texture *Dd* = drainage density *Fs* = stream frequency	km	Horton (1945)

	Form factor (*Ff*)	$Ff = \frac{A}{Lb^2}$ where: Ff = form factor A = area of watershed in km^2 Lb = basin length in km	unitless	Horton (1932)
Relief aspect	Elevation classes	Generated from QGIS	masl	ASTER-GDEM
	Slope classes	Generated from QGIS	%	ASTER-GDEM
	Relief ratio (*Rh*)	$Rh = \frac{Bh}{Lb}$ where: Rh = relief ratio Bh = total relief of the watershed in km Lb = basin length	unitless	Schumms (1956)
	Relative relief (*Rr*)	$Rr = \frac{He}{P}$ where: Rr = relative relief He = highest elevation in km P = perimeter of the basin (km)	unitless	Melton (1958)



Appendix II. Landslide occurrences in the Bued Watershed based on the satellite imagery (2017–2019) of Google Earth Pro (3D view).