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Morphometric Determinants of Dry Season Flow in Small Upstream Watersheds of Mts. Banahaw – San Cristobal Protected Landscape, Philippines

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Abstract: Geomorphology influences hydrologic response behavior of watersheds but seasonal responses such as dry season flow are rarely given focused more so their availability, quality, and spatiotemporal distribution. This is crucial for sustaining hydrologic ecosystem services (HES). This study assessed the influence of watershed morphometry on dry season flow volume and its selected physicochemical characteristics. Spot measurements of stream flow and its dissolved oxygen (DO), electric conductivity (EC), total dissolved solids (TDS), and Salinity levels from 56 small upstream watersheds in the Mts. Banahaw – San Cristobal Protected Landscape (MBSCPL) was determined. Principal Component Analysis (PCA) for variable reduction of geomorphological parameters and two-stage Random Forest Regression were used to determine the drivers of dry season flow occurrence and characteristics. Results showed that small upstream watersheds can exhibit sustained dry season flow with acceptable levels of EC, TDS, and Salinity. Total stream length (T_{lu}), Bifurcation ratio (R_b), area, and slope were the most important variables in predicting dry season flow volume, but its model showed poor validation performance and slightly overfit (R^2= 0.527, p = 0.011). Models for water quality parameters showed acceptable performance for DO, EC, Salinity, and TDS levels (R^2= 0.824, 0.713, 0.623, and 0.722, respectively) with flow volume (Q_{2018}) as the most important driver, followed by Basin relief (B_h), watershed area, and slope.

Keywords: Geomorphology; Morphometry; Dry season flow; Watersheds.

1 INTRODUCTION

Geomorphology encompasses features, such as drainage basins, channel characteristics (Chang, 2013), topographic landforms (Singh et al., 2010), morphology, and processes (Bachri et al., 2021), which can influence infiltration and spatial variations of surface runoff, including streamflow. Geomorphology is a crucial consideration in understanding hydrologic processes (Dávila-Hernández et al., 2022) within the watershed landscape, as it can serve as a constraint to the movement of water, solutes (ions dissolved in water), and particulate material from the headwaters to the watershed outlet (Covino et al., 2021). Morphometry is a systematic, quantitative, and mathematical analysis of geomorphology, topology, landforms, and the shape of the watershed (Vaidya et al., 2013; Kaur et al., 2014; Asfaw and Workineh, 2019; Khatoon and Javed, 2022). This analysis characterizes the linear, areal, and relief aspects of the watershed (Withanage et al., 2014). These features include stream order, stream length, mean stream length, stream length ratio, bifurcation ratio, mean bifurcation ratio, drainage density, drainage texture, form factor, ratio of circularity, ratio of elongation, length of overland flow, watershed relief, and relief ratio (Rendra et al., 2023).

Morphometric analysis assists in forecasting and understanding the response behavior of hydrological processes (Mahala, 2020; Kumar et al., 2021) and mitigating the impacts of unsustainable water use (Gajbhiye et al., 2014; Soni, 2017; Kabite and Gessesse, 2018; Abijith et al., 2020; Saha et al., 2022) and soil erosion (Chavare and Potdar, 2014; Khatoon and Javed, 2022; Benzougagh et al., 2022). This crucial role in understanding the hydrological response has been reported by Ayogu et al. (2019), Mahala (2020), Lopez-Ramos et al. (2022), and Andy and Ryntathiang (2023). Many studies have also employed morphometric analysis to assess flood risk and susceptibility, such as those by Pangali Sharma et al. (2024), Ahmed et al. (2022), and Rendra et al. (2023). Its application in flash flood susceptibility is particularly important in ungagged watersheds (Adnan et al., 2019; Obeidat et al., 2021; Saha et al., 2022). This analysis was also applied in assessing groundwater potential areas (Mahala, 2020; Barman et al., 2021; Benzougagh et al., 2022), site selection and design of structures for water resources conservation and sub-watershed prioritization (Dali et al., 2023). By prioritization, morphometric analysis allows managers and decision makers to design appropriate rehabilitation initiatives and target watersheds that can be most impactful in sustaining the soil and water supply efficiently.

Unfortunately, the seasonal hydrologic response of a watershed, such as dry season flow vis-à-vis its geomorphological characteristics, is rarely given focus. While climate is a strong driver (Hamel et al., 2017; Vicario et al., 2024) and changes in climatic variables alter water balance (Ruv Lemes et al., 2023), the role of geomorphology in groundwater storage and recharge during wet months, and groundwater discharge when rainfall is absent, is unclear. During the dry season, groundwater discharge sustains streamflow (Guidah Chabi et al., 2023). The reduction in flow volume may impair water quality, thereby reducing its economic and ecological value (Lupi et al., 2023) and the watershed's capacity to provide important HES. This can be critically important for upland communities dependent on small upstream watersheds for an available and accessible source of good-quality water supply. Generally, simulating dry season flow response to geomorphic characteristics is fundamentally important in ungauged watersheds (Saha et al., 2022).

This study assessed the role of geomorphology in the occurrence of dry season flow and its quality. The morphometry of the observed watershed was analyzed and used as a predictor variable for the occurrence, volume, and physicochemical characteristics of measured dry season flow. This study can provide insights into how geomorphology influences groundwater storage, recharge, and discharge in small upstream watersheds which can be crucial in prioritizing and planning for sustainable water resources conservation and management.

2 METHODOLOGY

2.1 Study site

Mts. Banahaw – San Cristobal Protected Landscape (MBSCPL) covers a land area of 10,900.59 hectares and is considered among the largest active volcanoes in the Philippines. It lies between 13º55' and 14º10' latitude and 121º16' and 121º35' longitude and is about 120 kilometers southeast of Manila. It is bounded by the Municipality of Majayjay and Laguna Lake on the north. The Municipality of Sariaya and the City of Tayabas border the southern portion. Laguna Lake and Tayabas Bay serve as the outlets for tributaries draining MBSCPL. The area covers a portion of 9 municipalities, including 2 cities in the provinces of Laguna and Quezon, and a catchment basin that provides potable water to more than 1 million people. Figure 1 shows the extent of MBSCPL and the communities in its surroundings.

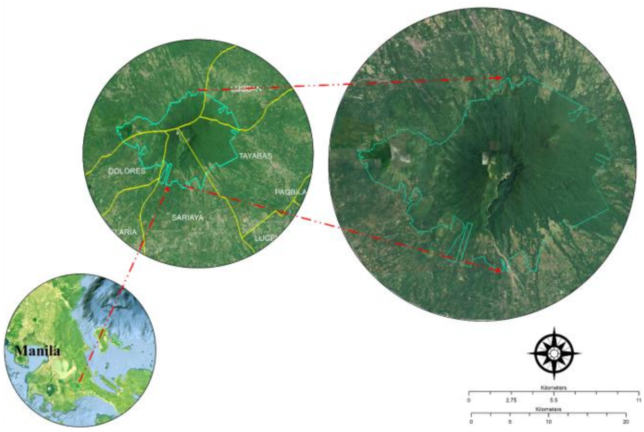

Fig. 1. Location of the study.

2.2 Watershed Characteristics

Rainfall, topography, and morphometric characteristics of small upstream watersheds draining MBSCPL were used as input for the analysis. MBSCPL was delineated into small upstream watersheds from the Digital Elevation Model (DEM) using Hydrology tools in GIS software. DEM with 30m resolution was accessed from the EarthExplorer website (https://earthexplorer.usgs.gov).

Rainfall Data. Rainfall data were requested from adjacent gauging stations. Additional rainfall data were requested from the Department of Science and Technology – Advanced Science and Technology Institute (DOST-ASTI) through the Freedom of Information website (https://www.foi.gov.ph) or downloaded from the Bureau of Soil and Water Management portal at (http://agromet.da.gov.ph). The spatial distribution of rainfall was spline-interpolated using Spatial Analyst tools in GIS software. Missing data at rain gauging stations was estimated through a linear regression model with its nearby stations. The mean 3-day rainfall before streamflow measurement was and used due to observed local variations in rainfall due to orography.

Geomorphology. The Department of Environment and Natural Resources (DENR, n.d.) describes geomorphometric parameters as physical features that characterize ruggedness, overall shape, drainage qualities, and the dissection of the watershed. Table 1 lists these geomorphometric parameters

2.3 Measurement of Dry-Season Flow.

Spot measurements of dry season flow were made in 56 catchments in May 2018, March 2020, and May 2021. During this period, streamflow is assumed to be at its lowest and most critical level in providing HES. The mean dry season flow from these 3 spot samplings was used in the analysis.

Stream Cross-sectional Area (A). To estimate ***A***, the width and average depth of the streamflow were measured. The average depth of the streamflow was measured at a 1-meter interval across the width of the river. The stream cross-sectional area was estimated using Eq. 1 below.

$$A = W * \mathrm{D} \tag{1}$$

Where A is the stream cross-sectional area (m^2); W is the width of the stream (m); D is the mean depth of the stream (m).

Stream Velocity (V). The stream velocity was estimated using Manning's formula given by Eq. 2. The slope of the stream was determined using an Abney hand level. Manning's roughness coefficient (n) was estimated by observing streambed characteristics, whether it is sand, gravel, or cobbles. The slope of the riverbed was used instead of the energy grade line, as the study assumed uniform flow in the streams (Ferguson, 2007; Zwolenik and Michalec, 2023), considering the low dry season flow measured at a level/flat section of the river. Thirty (30) samples of streambed materials were also collected to determine their average diameter and n values following Chang (2013).

$$V = \frac{R^{\frac{2}{3}} + S^{\frac{1}{2}}}{n} \tag{2}$$

Where: V is the mean stream velocity (m s^{-1}), R is the hydraulic radius (m); S is the Channel slope (%); and n is Manning's Roughness Coefficient.

The hydraulic radius (R) was computed as the ratio of the cross-sectional area of stream flow (A) to the wetted perimeter (P) using Eq. 3 below.

$$R = \frac{A}{P} \tag{3}$$

Where R is the hydraulic radius (m); A is the stream cross-sectional area (m^2); and P is the wetted perimeter (m).

Table 1. Measurement of geo-morphic parameters adopted from Watershed Characterization and Vulnerability Assessment using GIS and RS of DENR (n.d.).

PARAMETERS	FORMULA	DESCRIPTION	UNITS
A. Linear aspects			
1. Stream order (u)		Hierarchical rank	Dimensionless
2. Stream length (L_u)		Length of the major stream	km
3. Total stream length (T_{lu})		The sum of all L_u	km
4. Mean stream length (L_{sm})	$L_{sm} = L_u/N_u$	L_u = Total stream length of order ‘u’ N_u = Total number of stream segments of order ‘u’	km
5. Perimeter (P)			km
6. Stream length ratio (R_l)	$R_l = L_u/L_{u-1}$	L_u = Total stream length of order ‘u’ L_{u-1} = Total stream length of its next lower order	Dimensionless
7. Order length ratio (O_L)	$O_L = L_u/L_{u+1}$	L_u = Total stream length of order ‘u’ L_{u+1} = Total stream length of its next higher order	Dimensionless
8. Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$	N_u = Total number of stream segments of order ‘u’ N_{u+1} = Number of stream segments of the next higher order	Dimensionless
9. Mean bifurcation ratio	R_{bm}	Average of bifurcation ratios of all orders	Dimensionless
10. Basin length (L_b)			km
11. Rho coefficient (ρ)	$\rho = R_l/R_b$	Ratio of stream length ratio and bifurcation ratio	Dimensionless
B. Relief aspects			
12. Basin relief (B_h)	B_h = H–h	Vertical distance between the lowest and highest points	
13. Relief ratio (R_r)	$R_r = B_h/L_b$	Ratio of basin relief and length	Dimensionless
14. Ruggedness number (R_n)	$R_n = B_h \times D_d$	B_h = Basin relief D_d = Drainage density	Dimensionless
15. Melton’s Ruggedness number (MR_n)	$MR_n = B_h/A^{0.5}$	B_h = Basin relief A = Area of watershed	Dimensionless
16. Slope (S)	$S = (\Delta E/L)100\%$	$\Delta E = Elev_{max} - Elev_{min}$ along the principal flow path L = Length of the watershed along the main stream (by measuring the valley length and not the meandering curve)	%
C. Areal aspects			
17. Area (A)			km^2
18. Drainage density (D_d)	$D_d = T_{lu}/A$	Ratio of total stream length and area	km km^{-2}
19. Constant of channel maintenance (C)	$C = 1/D_d$	Inverse of drainage density	km km^{-2}
20. Circularity ratio (R_c)	$R_c = (4\pi A)/P^2$	A = Area of watershed P = Perimeter	Dimensionless
21. Elongation ratio (R_e)	$R_e = (2/L_b)[(A/\pi)^{0.5}]$	A = Area of watershed L_b = Basin length	Dimensionless
22. Compactness constant (C_c)	$C_c = P/(4\pi A)^{0.5}$	A = Area of watershed P = Perimeter	Km
23. Drainage texture (R_t)	$R_t = D_d \times F_s$	The product of drainage density and stream frequency	Km
24. Stream frequency (F_s)	F_s = N/A	Ratio between the total number of streams and the area	km^{-2}
25. Form factor (F_f)	$F_f = A/L_b^2$	A = Area of watershed L_b = Basin length	Dimensionless
26. Texture ratio (T)	$T = N_1/P$	Ratio of the total number of 1st order streams and perimeter	km^{-1}
27. Shape index (S_w)	$S_w = L^2/A$	L = Length of the watershed along the mainstream (by measuring the valley length and not the meandering curve)	Dimensionless
28. Shape factor (S_f)	$S_f = 1/F_f$	Reciprocal form factor	Dimensionless
29. Length of overland flow (L_g)	$L_g = 1/(2D_d)$	D_d = Drainage density	Km
30. Lemniscate ratio (K)	$K = L_b^2/4A$	L_b = Basin length A = Area of watershed	Dimensionless

Stream Discharge. Streamflow was estimated using the velocity–area method. The discharge is derived from the sum of the product of mean velocity, depth, and width between verticals. Stream discharge will be determined using Eq. 4 below.

$$Q = A \bullet V \quad (4)$$

Where Q is the stream discharge stream ($m^3 s^{-1}$); A is the stream cross-sectional area (m^2); and V is the mean velocity ($m s^{-1}$)

Dissolved Oxygen (DO), Electric conductivity (EC), Total Dissolved Solids (TDS), and Salinity were measured using the Hanna Instrument HI9828 in 2018.

2.4 Data Analysis

Principal Component Analysis and Random Forest Regression. Initially, the Principal Component Analysis (PCA) was used as a variable reduction technique for multicollinear predictor variables. The 1st stage of Random Forest regression (RFR) was applied to determine the most important predictor variable groups from the Principal Component (PCs) while the 2nd stage RFR was applied to identify individual predictors among the most important PCs. A backward regression was employed until an optimal model was attained. RFR was used to determine the important geomorphological features as determinants of dry season flow volume and physicochemical parameters.

3 RESULTS

3.1 Physiography and Geomorphometry

Figure 2 shows the 56 small upstream watersheds draining the MBSCPL sampled. The size, shape of the watershed, topography, and geomorphometry, such as ruggedness, overall shape, and drainage qualities influence rainfall partitioning, groundwater recharge, and ultimately, dry season flow. DENR (n.d.) grouped these geo-morphometric parameters into area, linear, and relief aspects of the watershed.

Area Aspects. A total catchment area of 170.8 km^2 with 57.8 km^2 (53.07% of the total 109 km^2) within MBSCPL was sampled. The mean area of all watersheds was only 3 km^2. About 34% of these had less than 5 km^2, and only 6 had more than 10 km^2 which are classified as catchments and small watersheds in the Philippine classification system.

The mean values of circularity ratio (R_c), elongation ratio (R_e), compactness coefficient (C_c), and form factor (F_f) were 0.222, 0.464, 2.302, and 0.190, respectively, all indicating that most of the watersheds sampled were more compact and elongated/elliptical than circular.

The mean D_d of all catchments sampled was considered high at 3.127 km km^{-2} (Barman et al., 2021) which can lead to more rapid runoff, less water storage, less groundwater recharge, and less dry season flow.

Linear Aspects. The majority (78.786%) of the observed catchments have 1st and 2nd order streams common in headwaters of mountainous watersheds (Jensen et al., 2017) and low R_b (mean = 3.285). The mean Stream Length (L_u), Total stream length (T_{lu}), stream length ratio (R_l), and *rho* coefficient for all catchments were 4.019 km (Sukristiyanti et al., 2018; Benzougagh et al., 2022), 9.178 km, 0.436, and 0.094, respectively. These linear aspects indicate low to moderate drainage.

Relief aspects. The mean values of Basin relief (B_h), relief ratio (R_r), Ruggedness number (R_n), and Melton's Ruggedness Number (MR_n) were 0.489 km, 0.095, 1.495 (Sharma et al., 2019; Barman et al., 2021), and 0.267, respectively, indicative of moderate relief features. B_h (Odiji et al., 2021) and R_r (Rawat et al., 2021) values also showed moderate relief and reflect terrain characteristics. R_n values of the catchments can be classified as having sharp morphology (Singh et al., 2010).

Rainfall Characteristics. Figure 3 shows the mean 3-day rainfall before the dry season flow measurement. The rainfall averages 17.924 mm for the years 2018, 2020, and 2021. Precipitation is the primary input to the water budget and influences the amount of moisture received, lost, recharge to groundwater, and groundwater discharge as dry season flow. The seasonal variations in runoff, precipitation, interception, and abstraction also influence the levels of sediment and nutrients in streamflow (Huang et al., 2016; Nafi'Shehab et al., 2021) affecting its water quality

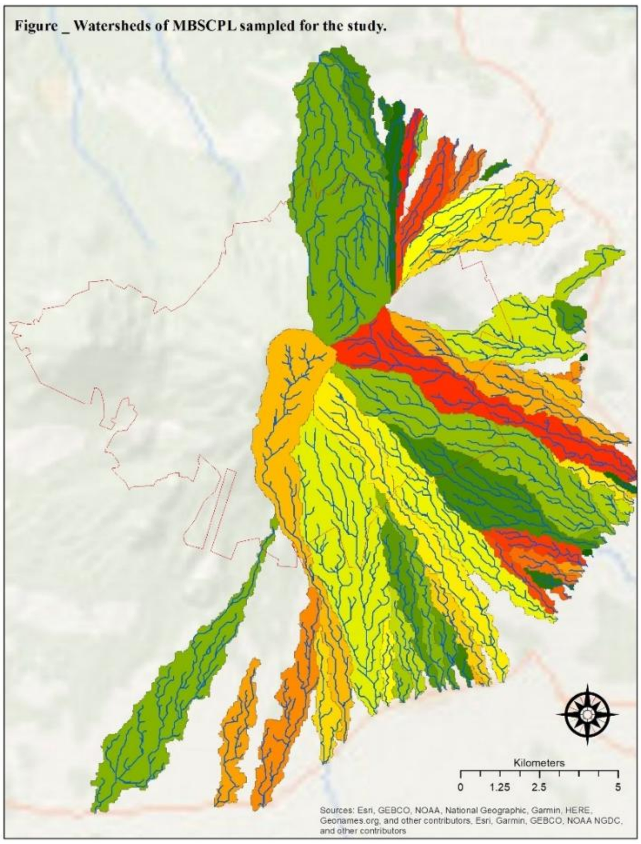

Fig. 2. Small upstream watersheds were sampled for the study.

3.2 Dry Season Flow in MBSCPL

Stream Discharge. Figure 4 summarizes the dry season flow of 56 small upstream watersheds from spot measurements in 2018, 2020, and 2021. Among 56 catchments, 39 had considerable flow (greater than 0.001 $m^3 s^{-1}$) during sampling. The total dry season flow averages 34.151 $m^3 s^{-1}$ for 3 years at an average of 0.876 $m^3 s^{-1}$. Kruskal–Wallis test revealed no significant differences between the observed dry season flow (H = 1.461 (3), p = 0.6912). This suggests the potential role of MBSCPL in enhancing groundwater storage, which can be discharged during the dry season (Romshoo et al., 2012; Abdulkareem et al., 2018).

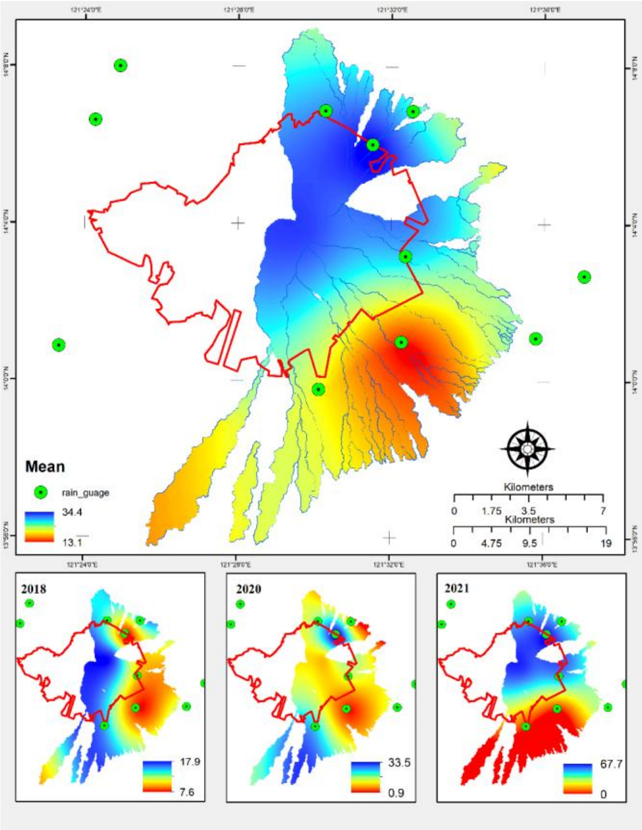

Fig. 3. The distribution of rain gauges and 3-day rainfall in 2018, 2020, and 2021.

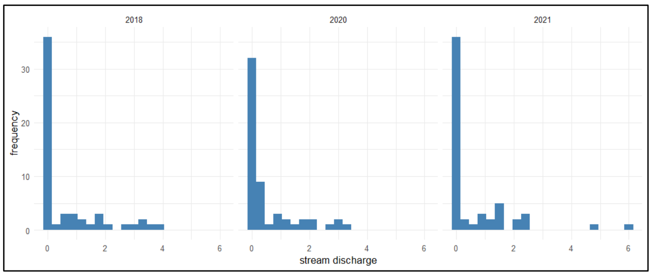

Fig. 4. Distribution of dry season flow in m^3 s^{-1} in MBSCPL.

Physicochemical characteristics of Dry Season Flow. Figure 5 shows DO, EC, TDS, and salinity levels during the dry season of 2018. The highest DO value recorded was 5.340 mg L^{-1} while the lowest was 2.740 mg L^{-1}. EC ranges from 79 µS/cm to 391 µS cm^{-1} while the salinity ranges from 30 mg L^{-1} to 180 mg L^{-1}. The TDS ranges from 40 ppm to 195 ppm. These observed values also exhibited high variability and non-normal distribution.

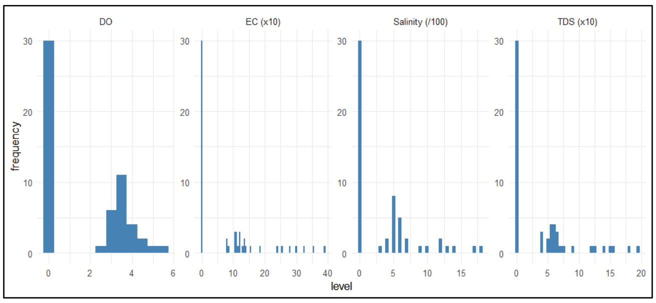

Fig. 5. Levels of DO (mg L^{-1}), EC (µS cm^{-1}), TDS (ppm), and Salinity (mg L^{-1}) from Q_{2018}.

3.3 Watershed Geomorphology - Dry Season Flow Relation

Principal Component. PCA reduced the 30 geomorphic parameters into 7 PCs or predictor groups consisting of the 3 PCs for area, 3 for linear, and 1 for relief aspects which captures 90.467%, 89.496%, and 88.699% variability, respectively. PCs for area aspects included: 1) *watershed shape* ($PC1_{area}$ associated with the Constance of channel maintenance (C), shape index (S_w), shape factor (S_f), and Lemniscate ratio (K) with 0.420, 0.407, 0.402, and 0.402 eigenvectors, respectively); 2) *watershed area* ($PC2_{area}$ highly associated with catchment area with 0.904 eigenvectors); and 3) *drainage-area relation* ($PC3_{area}$ associated with Texture ratio (T), Stream frequency (F_f), and Drainage texture (R_t) with 0.633, –0.578, and –0.453 eigenvectors, respectively).

PCs for linear features included: 1) *drainage length and network* (PCs associated with total stream length (T_{lu}), and Bifurcation ratio (Rb) with 0.505 and 0.435 eigenvectors, respectively); 2) *drainage order –length relation* ($PC2_{linear}$ associated with the *Rho* coefficient, order length ratio (O_L), stream length ratio (R_l), and T_{lu}, these parameters had 0.405, –0.386, 0.373, and –0.362 eigenvectors, respectively); and 3) *drainage length* ($PC3_{linear}$ associated with meal stream length (L_{sm}), stream length ratio (R_l), and order length ratio (O_L) eigenvectors, respectively).

PCs for relief features included *relief index* ($PC1_{relief}$ associated with basin relief (B_h), ruggedness number (R_n), relief ratio (R_r), and *slope* with 0.485, 0.462, 0.460, and 0.443 eigenvectors, respectively).

Morphometry – Streamflow Volume Relation. Table 2 summarizes the importance of geomorphic predictor groups to dry season flow volume. Overall, *drainage length and network*, *watershed area*, *relief index*, and *drainage length* accounted for 71% importance in the prediction. The high importance of T_{lu} and R_b in drainage length and network indicates the role of flow path length and permeability of the watershed in dry season flow generation. This was further emphasized by the drainage length associated with L_{sm}, R_l, and O_L as 4th highest important PCs.

After the 2nd stage of RFR revealed that total stream length (T_{lu}), Bifurcation ratio (R_b), *area*, and *slope* were the most important individual predictors for dry season flow. The R^2 and median R^2 values for training and validation were 0.815 ($p < 0.000$) and 0.527 ($p = 0.011$) at 73,672 random seed numbers. This indicates slight overfitting and poor performance of the model for the prediction of dry season flow volume.

Morphometry – Water Quality Relation. Tables 3 and 4 summarize the importance of geomorphic predictor groups, rainfall (*3–day rainfall*), and flow volume (Q_{2018}) to DO, EC, Salinity, and TDS. Overall, results showed that Q_{2018} had the highest importance in predicting physicochemical parameters. For predictor groups, *drainage length and network* ($PC1_{linear}$) were important in EC, Salinity, and TDS. *Relief index* ($PC1_{relief}$) and *watershed area* ($PC2_{area}$) also showed relatively high importance in predicting water quality. For the individual predictor, Q_{2018} remained the most important parameter for predicting the quality of dry season flow. The *slope of the watershed* and B_h were important for predicting EC and TDS. The *area of the watershed* was important for predicting levels of Salinity and TDS. The models had acceptable performance for all water quality parameters. Figures 6 and 7 compare the observed and modeled dry season flow characteristics and projections for MBSCPL, respectively.

Table 2. Importance of different geomorphologic predictor groups and rainfall as predictors of dry season flow.

Variable	Description	Importance	% Importance	Rank
$PC1_{linear}$	*drainage length and network* is associated with total stream length (T_{Lu}), and Bifurcation ratio (R_b)	10.72	25	1
$PC2_{area}$	*watershed area* is associated with the area of the watershed, circularity ratio (R_c), length of overland flow (L_g)	7.43	17	2
$PC1_{relief}$	*relief index* is associated with basin relief (B_h), ruggedness number (R_n), relief ratio (R_r), and slope	6.44	15	3
$PC3_{linear}$	*drainage length* is associated with mean stream length (L_{sm}), stream length ratio (R_l), and order length ratio (O_L).	5.89	14	4
3-day Rainfall	3–day rainfall before streamflow measurements	4.00	9	5
$PC1_{area}$	*watershed shape* associated with total Drainage texture (R_t)	3.51	8	6
$PC2_{linear}$	*drainage order–length relation* is associated with the *Rho* coefficient, order length ratio (O_L), stream length ratio (R_l), and Total stream length (T_{lu}).	2.66	6	7
$PC3_{area}$	*drainage-area relation* is associated with shape index (S_w), shape factor (S_f), and Leminiscate ratio (K)	2.10	5	8

Table 3. The importance of geomorphic predictor groups as predictors of DO, EC, TDS, and salinity levels.

Predictor Variable	DO		EC		TDS		Salinity	
	% Importance	Rank	% Importance	Rank	% Importance	Rank	% Importance	Rank
3-day Rainfall	5	5	7	4	4	8	8	5
Q_{2018}	55	1	50	1	43	1	47	1
$PC1_{area}$	7	3	3	8	6	5	4	7
$PC2_{area}$	5	4	10	3	7	4	9	3
$PC3_{area}$	4	6	5	6	5	6	3	8
$PC1_{linear}$	4	8	11	2	16	2	14	2
$PC2_{linear}$	4	7	2	9	4	7	4	6
$PC3_{linear}$	2	9	4	7	2	9	2	9
$PC1_{linear}$	15	2	7	5	14	3	9	4
R^2 (Training)	0.97		0.91		0.92		0.94	
R^2 (validation)	0.83		0.63		0.65		0.69	
MSE_{100}	0.860		4936.331		0.001		1664.070	
% Variation Explained	75.475		37.865		54.663		40.752	

Table 4. Importance of geomorphic predictor variables in the levels of DO, EC, TDS, and Salinity.

PARAMETER	% VARIABLE IMPORTANCE			
	DO	**EC**	**Salinity**	**TDS**
Q_{2018}	50	40	54	46
T_{lu}	−	−	22	−
area	−	−	25	13
slope	17	21	−	11
3-day Rain	17	16	−	−
R_c	−	−	−	−
L_g	−	−	−	−
R_r	16	−	−	−
R_n	−	−	−	−
R_b	−	−	−	−
B_h	−	22	−	15
R^2 (training)	0.969	0.933	0.896	0.928
R^2 (validation)	0.824	0.713	0.623	0.722
MSE_{100}	0.889	5445.891	0.001	1216.569
%Variation explained	73.911	53.534	57.016	55.060

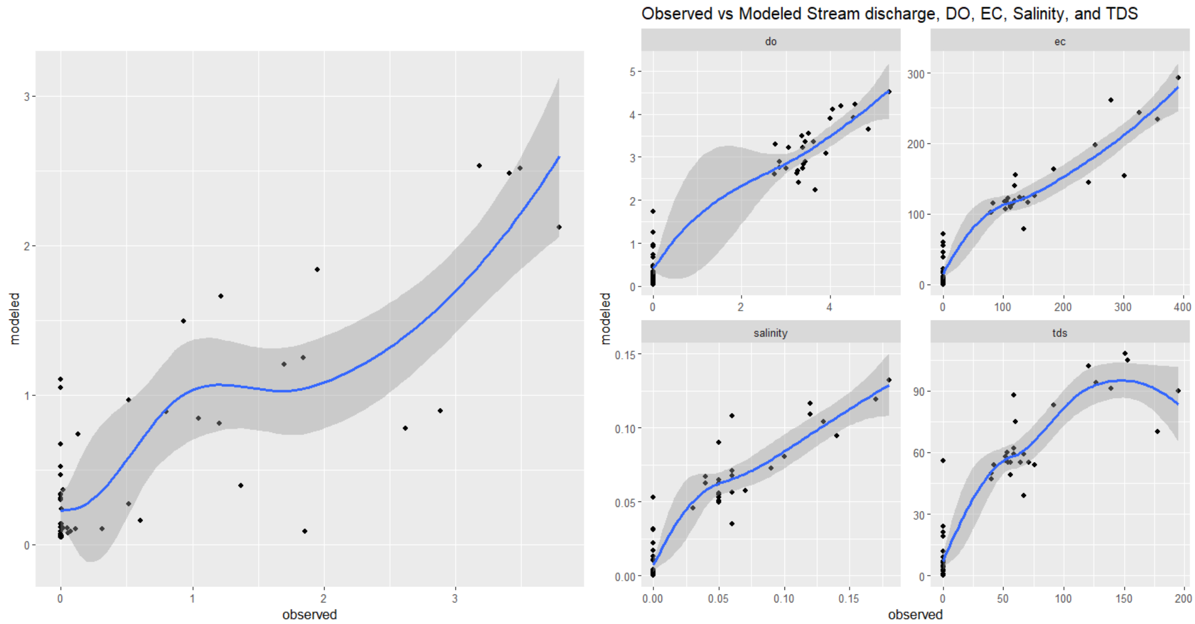

Fig. 6. Observed vs Modeled streamflow volume (m^3 s^{-1}) and water quality parameters of MBSCPL.

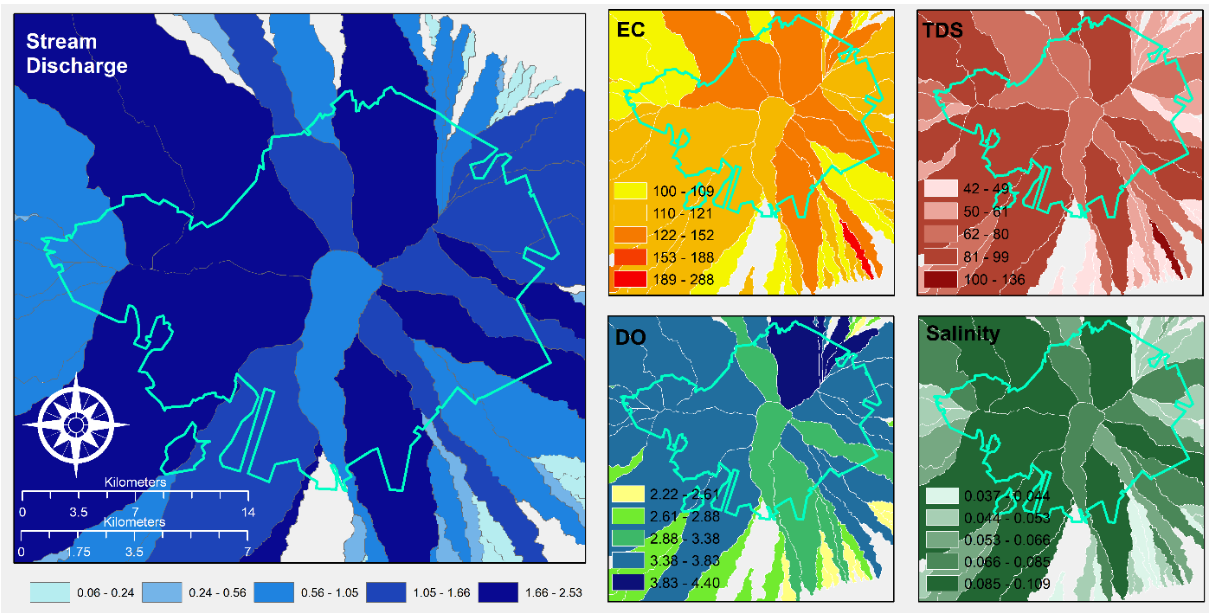

Fig. 7. Projected streamflow volume (m^3 s^{-1}) and water quality parameters of MBSCPL.

4 DISCUSSION

4.1 Temporal variations of scour depth

Area Aspects. The small upstream watersheds of MBSCPL only average 3 km^2, which influences how much rainfall can be collected (Aboelnour et al., 2021) and contributes to the surface run-off that drains into the rivers and ultimately the amount of groundwater recharged that can be released during the dry season. These watersheds were found to be elongated (mean R_c = 0.223, mean R_e = 0.464, F_f = 0.190) and more compact, like the findings of Abdulkareem et al. (2018), Bachri et al. (2021), Kumar et al. (2021), and Rendra et al. (2023). These can be attributed to the slope of these small upstream watersheds, which is expected in mountainous terrains like MBSCPL. Steeper slopes in these catchments can increase the flow of water downhill, resulting in longer stream channels with less branching and elongated watersheds. Elongated watersheds have greater surface area, are more exposed, and capture more rainfall, but may have delayed stream flows since there are longer flow paths and more water loss to evaporation. This is in addition to high C_c, which also indicates delayed peak flows in streams.

Linear Aspects. The small upstream watersheds of MBSCPL generally showed low to moderate permeability. The mean value of R_b in the study area was 3.285, like the findings of Soni (2017), Abdulkareem et al. (2018), Bachri et al. (2021), Kumar et al. (2021), and Rendra et al. (2023) in small watersheds, but has a wider range of values (1 to 12) in this study. This was because many (46% of the total) of the small watersheds sampled were 1st order streams from the headwaters, with only 4% being 4th order streams. This finding also aligned with previous results, such as Asfaw and Workineh (2019), Kumar et al. (2021), Rendra et al. (2023), Bachri et al. (2021), and Khatoon and Javed (2022), that stream orders and numbers increase with increasing basin area. Furthermore, the increased interconnectedness of these small upstream watersheds (D_d of 3.127 km^{-2}) may lead to more rapid runoff since there are more channels available for water to flow through, increased sediment loads with more water flowing over the land, and increased erosion and sedimentation. Hence, there is less water storage, less groundwater recharge, and less dry season flow.

Relief aspects. Results indicated moderate relief (Odiji et al., 2021) in these small upstream watersheds, which are similar to the findings of Soni (2017), Abdulkareem et al. (2018), and Bachri et al. (2021). This low variation of topographic features, such as elevation and slope, may be expected from smaller watersheds. B_h (R^2 = 0.572) and R_r (R^2 = 0.842) had linear correlations with the area of the small upstream watershed in MBSCPL. In contrast, higher reliefs were reported by Romshoo et al. (2012) and Ismail et al. (2022) at watersheds with at least 1,200 km^2 of basin area. This implies that higher variability can be captured at bigger watersheds, increasing variability in their relief aspects.

4.2 Geomorphometric Determinants of Dry Season Flow

Drivers of Dry Season Flow Volume. The total stream length (T_{lu}), Bifurcation ratio (R_b), *area*, and *slope* were the most important individual predictors for dry season flow. Similarly, the *slope* of the small watershed was also reported by Owen and Pavlowsky (2011) and Andy and Ryntathiang (2023) to influence dry season flow by rapid stormflow response and reduced dry season flow. In addition, the *slope* influences infiltration, surface runoff generation, and groundwater recharge. While Wu et al. (2021) reported similar findings that R_b is among the key factors to streamflow generation in small watersheds, the role of R_b is more commonly reported at bigger watersheds, such as Soni (2017), Asfaw and Workineh (2019), and Khatoon and Javed (2022). The low *Rb* (mean = 3.285) in MBSCPL may have contributed to lower time-to-peak discharge and the possibility of flooding during rain events (Romshoo et al., 2012; Abdulkareem et al., 2018) resulting in lower groundwater recharge and dry season flow.

In comparison, the importance of the *area* of the small upstream watershed and T_{lu} in streamflow generation was not identified from these previous studies. Instead, their importance may be reflected in a combination through drainage density ($D_d = T_{lu}/A$). *Dd* of MBSCPL was generally high (mean D_d = 3.127 km km^{-2}, mean T_{lu} of 9.178 km, mean *area* = 3 km^2) compared with the works of Abdulkareem et al. (2018), Kumar et al. (2021), Rendra et al. (2023), and Soni (2017), who reported approximately the same values on small watersheds that are more than double in size. This difference may be associated with the identification of streams from DEM and the threshold set for the length of streams. In this study, streams with at least 500 meters in length were considered, except for some very small watersheds sampled.

The small size of these upstream watersheds means less rainfall can be captured, converted to surface runoff, infiltrate, percolate, and recharge the groundwater (Aboelnour et al., 2021), and consequently, groundwater discharge during the dry season. The presence of many streams (Lu) indicates low permeability and infiltration as influenced by the catchment's physiographical, geomorphological, and geological features. This may explain why 30% of all small upstream watersheds in MBSCPL did not exhibit dry season flow. Sustaining dry season flow can become more critical for these watersheds with a small catchment area.

Drivers of Dry Season Flow Quality. For individual predictors, the volume of streamflow (Q_{2018}), area, and slope of the watershed were among the most important predictor variables for physicochemical properties of dry season flow. The dominance of streamflow volume aligns with the findings of Owen and Pavlowsky (2011) and Wu et al. (2021). The high importance of Q_{2018} in water quality (Guo et al., 2019) may be expected since the amount of water determines its capacity to buffer and dilute concentrations of pollutants. Hence, the concentration of pollutants and nutrients in water may increase (Patil et al., 2022) as flow volume falls during the dry season. During this period, sediments along the stream bed (Stefanidis et al., 2019) from eroded soils in agricultural areas and effluents from households may have contributed to the water quality in the small upstream watershed of MBSCPL. Chemicals may be liberated from these sediments in the stream bed (Kamarudin et al., 2019) into dissolved bioavailable forms (Fu et al., 2020). Hence, pollutants and sediments deposited in stream channels during rain events may influence water quality during the dry season.

In terms of morphometry, the *area* and *slope of the watershed* were among the most important predictors, contrary to D_d and *Rr* reported by Wu et al. (2021) and Rendra et al. (2023), although these studies reported D_d and R_r were found to influence water quality through nutrient export and sediment load during low flow and storm periods. In MBSCPL, the *slope of the watershed* was also important for predicting DO, EC, and TDS, while B_h was important in predicting EC and TDS. The *area of the watershed* was important for predicting levels of Salinity and TDS. The differences in observed predictors in this study and those of Wu et al. (2021) and Rendra et al. (2023) may be associated with the differences in the number and variability of watersheds studied. This study used 56 small upstream watersheds with areas varying from 0.048 km^2 to 20.565 km^2, which might be captured in RFR and yielded as among the important predictors. This study also identified stream channels using a 30m resolution DEM, which may differ from previous studies.

The influence of relief features, such as *slope of watershed* and B_h, on variability of water quality has also been reported in many studies, like Almada et al. (2019), and can be secondary to landscape characteristics and land cover, such as the findings of Bhattacharya et al. (2020), Wu et al. (2021), and Xu et al. (2023). This reported dominance of landscape characteristics over relief features may be possible since the surface runoff dissolves and transports pollutants and nutrients towards and along stream channels as it moves across these various landscape compositions and configurations. These land cover types can be point sources of pollutants to streams. The *slope of the watershed* and its B_h influence water quality (Aulakh et al., 2025) differently. They influence the flow of water and allow self-purification, oxygenation, dissolution of pollutants (Guananga et al., 2022) and ultimately flush them out of the watershed. Although this influence may vary depending on scales (Yan et al., 2023), relief features can affect the residence time of nutrients and pollutants in the watershed. A steeper slope leads to faster streamflow and promotes flushing of nutrients and pollutants, thereby improving water quality.

4.3 Watershed geomorphometry and sustainable landscape

Dry season flow may indicate sustainability in watersheds. This landscape should provide for the water supply demands of society while maintaining good ecological integrity. HES can become more critical for upland communities dependent on surface water for water supply during the dry season. Climate-resilient watersheds provide a fresh water supply for communities and ecosystems despite these challenges.

The observed resemblance between dry and wet season flow may indicate the resiliency of small upstream watersheds in MBSCPL. In addition, the observed EC, Salinity, and TDS did not exceed limits for drinking water set by DENR in the Philippines nor the World Health Organization (WHO). DO ranged from 2.740 to 5.340 (average 3.6 $\pm$ 0.7 mg L^{-1} SD) but exceeded water quality limits of 5 mg L^{-1} and indicated an insufficient amount of oxygen in the water. This means that these small upstream watersheds are not contaminated but biologically impaired to support aquatic organisms.

The *watershed area* was an important determinant of the volume (although the model slightly overfitted) and physicochemical characteristics of dry season flow. However, the observed watersheds only included small upstream watersheds forming recharge areas in the headwaters, and results may not be sufficient for generalization, especially for larger watersheds. In addition, even if there is effective groundwater recharge in the small upstream watersheds, they may not exhibit dry season flow; instead, groundwater may discharge at a mid or downstream section further from these recharge areas. As watershed size increases, variation and complexities in physiography, soil, climate, and their interaction also increase. Understanding area-dry season flow relationships needs to be further studied. Nonetheless, this study showed that small upstream watersheds are an important consideration in ensuring sustainable water supply. Furthermore, the *drainage length and networks* were also important determinants, and *drainage patterns* may be used as an indicator of a sustainable watershed landscape. Small upstream watersheds that favor infiltration, deep percolation, and groundwater recharge tend to develop few but long streams and may exhibit sustained streamflow. Improving infiltration, percolation, and groundwater recharge contributes to the sustainability of the watershed landscap.

5 CONCLUSION

Dry season flow can be critically important in providing HES; hence, understanding its behavior is vital. Assessing eco-hydrologic processes and systems governing dry season flow can be challenging since these can be inherently dynamic and complex in addition to the spatial heterogeneity of their driving forces. This study assessed the influence of geomorphic features of the watershed on its dry season flow volume and selected physicochemical characteristics. Geomorphic characterization revealed that most of these small upstream watersheds were more compact and elongated/elliptical than circular, with low to moderate drainage and permeability, and moderate relief features. Small upstream watersheds may also exhibit non-contaminated and sustained dry season flow but be biologically impaired. Overall, the *drainage length and network*, *watershed area*, and *relief index* were among the most important geomorphic predictor groups, with *area* and *slope* of watershed as important predictors for dry season flow. In addition to *area* and *slope*, T_{lu} and R_b were among the most important for flow volumes. The volume of flow (Q_{2018}) was also the most important predictor for DO, EC, Salinity, and TDS levels in water, followed by B_h.

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