Journal of Environmental Science and Management Special Issue 1-2023: 1-13 ISSN 0119-1144

Development of Synthetic Unit Hydrographs Using Spatial Proximity Regionalization for the Makiling Forest Reserve, Philippines

ABSTRACT

There is a dearth of streamflow data in the Philippines to generate hydrographs needed for flood forecasting and water resources assessment. A method of generating and calibrating synthetic hydrographs using model simulations and spatial proximity regionalization is presented. Synthetic unit hydrographs of four storm events in the gauged watershed of Makiling Forest Reserve were generated using Soil Conservation Service Unit Hydrograph, Clark Unit Hydrograph, and Snyder's Unit Hydrograph methods. The generated synthetic hydrographs for each runoff modeling technique were calibrated with the actual hydrographs of the watershed. Snyder's Unit Hydrograph model results were the most acceptable based on the Nash-Sutcliffe Efficiency, Index of Volumetric Fit, and Relative Error of Peak Flow. The weighted values of the calibrated watershed parameters computed using spatial proximity regionalization technique and the hyetographs derived from the Rainfall Intensity Duration Frequency Curve of the University of the Philippines Los Baños-National Agrometeorological Station were used to generate the synthetic unit hydrographs for three neighboring ungauged watersheds at 2-, 5-, 10-, 15-, 20-, 25-, 50, 100-year return periods. Total runoff volume, the magnitude of peak flows, and time to peak derived from the generated hydrographs can be used in watershed planning, water resources management, flood forecasting and the design of various water control structures.

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Keywords: *spatial proximity regionalization, synthetic unit hydrograph, SCS, Clark, Snyder, Makiling Forest Reserve*

INTRODUCTION

The Philippines experiences approximately 20 typhoons per year, five of which are destructive and cause flooding and landslides (*Lapidez et al. 2015*). These typhoons cause major damage to agriculture, cripple industries, displace communities, and claim lives. To be able to prevent damages or lessen the risk of fatalities caused by these hazards, the government continuously implements different public work projects (e.g., construction of flood control structures, dikes, and drainage systems). The design of these projects requires determining the design flow generated from streamflow hydrographs.

A hydrograph is a plot of a stream discharge with time measured at an outlet of a certain watershed. It describes the catchment's response to a rainfall event. These graphs are generated using discharge data acquired through gauging instruments such as calibrated Parshall flumes and other flow-measuring structures. Hydrographs can be developed for both gauged and ungauged basins. For gauged basins, observed data of concurrent rainfall and streamflow discharges for any storm events can be used in generating hydrographs (*Singh et al. 2014*). In the Philippines, a limited number of rivers are installed with gauging instruments in the Philippines resulting in inadequate streamflow data needed for generating hydrographs.

One empirical model that is used to describe the relationship between direct runoff (DRO) and excess rainfall in a watershed is the unit hydrograph (UH). First proposed by *Sherman* (*1932*), a UH is the "basin outflow resulting from one unit of direct runoff generated uniformly over the drainage area at a uniform rainfall rate during a specified period of rainfall duration." Its essence is that since the basin's physical characteristics that govern flow (e.g., shape, size, slope, etc.) are constant, it is reasonable to assume that DRO from rain events of the same duration will have the same shape and base time (*Linsley et al. 1982; Subramanya 2008*). The derivation of the UH, its linear systems theory, and the procedures for several UH methods can be found in hydrology literature

(*Chow et al. 1988; Linsley et al. 1982; Viessman and Lewis 2003*).

Streamflow data for many watersheds are seldom available or incomplete for a wide range of storm durations and rainfall depths causing difficulty in DRO computation with specified UH. An alternative is the use of parametric UH which defines only the important UH properties such as peak flow, time to peak, or base time, using one or more equations (*Huang et al. 2008*). A synthetic UH relates these parameters to watershed physical characteristics which could easily be measured or determined. In this aspect, spatial and topographical analysis of various watersheds is essential (*Ternate et al. 2017*).

Numerical simulations are used to generate synthetic UH for ungauged watersheds when insufficient data or concurrent observations of rainfall and streamflow discharges are not available (*Gunawardhana et al. 2020*). It is derived by simulating flow within the basin through the estimation of lag times between rainfall and discharge without using actual rainfall-runoff data (*Tunas et al. 2019*). Synthetic unit hydrograph methods are based on a theoretical or empirical formula relating peak flow, peak time, and base time to the physical characteristics of a watershed (*Bedient et al. 2008; Bhunya et al. 2011*).

The development of synthetic UH requires various assumptions, specifically the time of concentration, lag time, slope, land use, soil type, and rainfall intensity of a certain location. Although synthetic UH gives a reasonable estimate of the discharge of a certain river, the generated discharge values vary depending on the runoff modeling technique used (*van Dijk et al. 2014*). Thus, it is important to choose the best modeling technique that is suitable for a certain catchment basin.

One method for developing the synthetic UH of a watershed is by using spatial proximity regionalization. This method utilizes the watershed parameters or characteristics of a gauged watershed, which is adapted to its neighboring watersheds, assuming that these watersheds have similar climatic and geophysical attributes (*Clanor et al. 2016; Lebecherel et al. 2016*). These watershed parameters will be used to simulate the rainfall events in the ungauged watersheds to generate synthetic UH for every return period.

Most studies in determining the synthetic UHs of a certain catchment basin use several runoff modeling techniques (*Razavi and Coulibaly 2013*). These methods can be compared using several hydrologic model criteria that relate the different characteristics of a synthetic to the actual hydrograph (*Brunner et al. 2017*). Synthetic hydrographs are created for the benefit of the ungauged watersheds to have an accurate estimation of the discharge and other hydrograph characteristics including time to peak, point of rising, the endpoint of recession, and total volume of runoff (*Kim et al. 2019*).

Despite significant progress in regionalization methods, it is impossible to identify a single approach that is the most effective for all watersheds *(Razavi and Coulibaly 2013; Lebecherel et al. 2016*). A specialized study must be carried out on every area of interest to determine which method is most suitable (*Samuel et al. 2012; Li et al. 2014; Waseem et al. 2015; Garambois et al. 2015*). It is hoped that this study will show that spatial proximity regionalization will be suitable for small ungauged watersheds with high rainfall occurrence. After model calibration and validation, the generated synthetic hydrographs can be used to estimate the total volume of runoff, time to peak, and time to recede for the ungauged watersheds.

A catchment basin with a gauging instrument that can generate an actual hydrograph of a rainfall event is a suitable site to determine the synthetic hydrographs of its neighboring watersheds. In this study, the Makiling Forest Reserve (MFR) was selected as the study site. It has a streamflow gauging instrument and an automatic rainfall recorder that can be used to test and compare the runoff models. Comparative testing will aid in determining the best runoff modeling technique suitable for the neighboring catchment basins of the MFR. Synthetic UH of the MFR can be developed for different return periods which can then be used to generate hydrographs needed in watershed planning, water resources management, flood forecasting, irrigation, and dam design, among others.

MATERIALS AND METHODS

Research Site

Mount Makiling is a 1,090 m dormant volcano situated between the municipalities of Calamba, Los Baños and Bay in Laguna province, and the municipality of Sto. Tomas in Batangas province (*Sandoval and Tiburan 2019*). The Makiling Forest Reserve (MFR) was established as a training laboratory for scientists and foresters to preserve the living ecosystems and acquire various data for the development of the forest in this mountain (*Cledera-De Los Santos et al. 2021*). Among the many watersheds draining from the MFR, only the Molawin Creek watershed is gauged, making it an ideal site for spatial proximity studies for the four adjacent watersheds.

Data Collection

The data required to generate the synthetic unit hydrographs for the MFR include the streamflow data of the gauged watershed, rainfall data, digital elevation model (DEM), soil and land cover maps, and the Rainfall Intensity Duration Frequency (RIDF) curve. Actual discharge data of the Molawin Creek was acquired from the University of the Philippines Los Baños - College of Forestry and Natural Resources (UPLB-CFNR), which maintains a streamflow gauging facility at the Makiling Botanical Garden. Data includes discharges at 10-minute intervals covering the period from one day before the arrival of the storm in the area to one day after the departure of the storm (**Table 1**).

Rainfall data for each storm event were obtained from the National Agrometeorological Station of UPLB. Taking into account the reduction of the rainfall intensity with the watershed area, point-rainfall data at the station were transformed into basin mean rainfall using Horton's Formula as shown in Equation 1.

$$r = r_o * e^{\left[-0.1(0.386A)^{0.31}\right]} \tag{1}$$

where:
r is the basin mean rainfall (mm)
r_o is the point rainfall (mm)
A is the catchment area (km^2)

The RIDF curve of Los Baños, Laguna generated using 17 years of rainfall data was acquired from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). The rainfall depth for each return period (2-, 5-, 10-, 15-, 20-, 25-, 50-, 100-year) of the RIDF Curve and the transformed rainfall intensity values were used as input hyetographs in the simulations using HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System).

A 5-m × 5-m resolution Digitial Elevation Model (DEM) of the MFR was acquired from the National Mapping and Resource Information Authority (NAMRIA). The land cover and the soil maps were acquired from the *Makiling Center for Mountain Ecosystem* (*2016*). Quantum Geographic Information System (QGIS) 2.18 Las Palmas was used to delineate and subdivide the watersheds of the MFR. Pertinent watershed characteristics such as the watershed area, slope, and longest flow length of the river, as well as model parameters like hydrologic soil group (HSG), runoff curve number (CN), initial abstraction (Ia), and potential maximum retention (S), were generated from these inputs.

Table 1. The four storm events that generated the discharge data at Molawin Creek used in the study.

Typhoon Local Name	Typhoon International Nname	Date
Odette	Khanun	October 11-14, 2017
Emong	Nanmadol	July 1- 4, 2017
Salome	Haikui	November 8 -10, 2017
Ompong	Mangkhut	September 13 -15, 2018

Development and Calibration of Runoff Models

Generation of synthetic UH includes the process of runoff simulation using various techniques. The Soil Conservation Service (SCS), Clark, and Snyder's UH methods were used in this study. These empirical models are all categorized as event, lumped, and fitted-parameter models These mean that each model simulates a storm event individually while disregarding or averaging spatial differences, and establishes its parameters by fitting the model with observed values (*US Army Corps of Engineers 2000*). The synthetic UH of each runoff modeling technique for the four storm events was generated using the basin model of the Molawin Watershed, the specific watershed parameters, and the input hyetographs of each storm event. The simulation process in HEC-HMS used SCS, Clark and Snyder's UH to generate hydrographs for MFR (**Figure 1**).

SCS Unit Hydrograph. The SCS unit hydrograph is a dimensionless, single-peaked UH that was created by the SCS in 1975. It accounts for the land use, flow regime, UH, and the hydrologic soil group of a certain watershed (*Dan-Jumbo and Metzger 2019*). These parameters are abridged in a certain value called the Curve Number (CN) which accounts for the approximate estimation of the effects of the said parameters (*U.S. Department of Agriculture 1972*). The required input values in HEC-HMS are the time of concentration (Equation 2) and the lag time (Equation 3).

$$T_c = L^{0.8} * \frac{\left[\left(\frac{1000}{N}\right) - 9\right]^{0.7}}{4407 * S^{0.5}} \tag{2}$$

$$T_L = T_c * 0.6 \tag{3}$$

where:
T_c is the time of concentration (h)
L is the longest flow length (m)
N is the runoff curve number
S is the average watershed slope (m m^{-1})
T_L is the lag time (h)

Clark Unit Hydrograph. Clark's method of UH construction is based on a linear channel and a linear reservoir (*Che et al. 2014*). It expresses channel routing (translation) based on synthetic time-area curves and attenuation using linear reservoir routing (*US Army Corps of Engineers 2001*). The time of concentration for each watershed in the Clark Unit Hydrograph was computed using Equation 4.

$$T_c = 0.4444A^{0.4867}(L/S)^{0.4868} \quad (4)$$

where
T_c is the time of concentration (min)
A is the area of the watershed (m^2)
L is the longest flow length (km)
S is the average watershed gradient ($m\ m^{-1}$)

$$R = T_C/(1.46\ - 0.0867\ * (L\hat{}2/A)) \quad (5)$$

where
R is the storage coefficient
A is the area of the watershed (m^2)

Snyder Unit Hydrograph. *Snyder* (*1938*) developed a set of empirical equations for synthetic UH from studies of ungauged watersheds in the Appalachian Highlands in the US. Lag time, peak flow, and total base time were selected as critical UH parameters. Rainfall duration, T_r, is related to the lag time by the equation $T_r=T_L/5.5$. The lag time and peak discharge for a given watershed are computed using Equations 6 and 7, respectively.

$$T_L = C_1C_t(LL_C)^{0.3} \quad (6)$$

$$Q_p = C_2C_pA/T_L \quad (7)$$

where
T_L is the lag time (h)
C_1 is a conversion constant (0.75 for SI and 1.0 for English units)
C_t is the watershed coefficient (0.4 for mountainous site)
L is the length of the mainstream from the outlet to the divide (m)
L_C is the length along the mainstream to a point nearest the watershed centroid (m)

The values of runoff curve number, initial abstraction, and the respective value inputs for each runoff modeling technique were calibrated using the Optimization Tool of HEC-HMS. The calibration procedure was conducted using the Simplex Method with a maximum value of iterations equal to 1000 and a value of tolerance equal to 0.01.

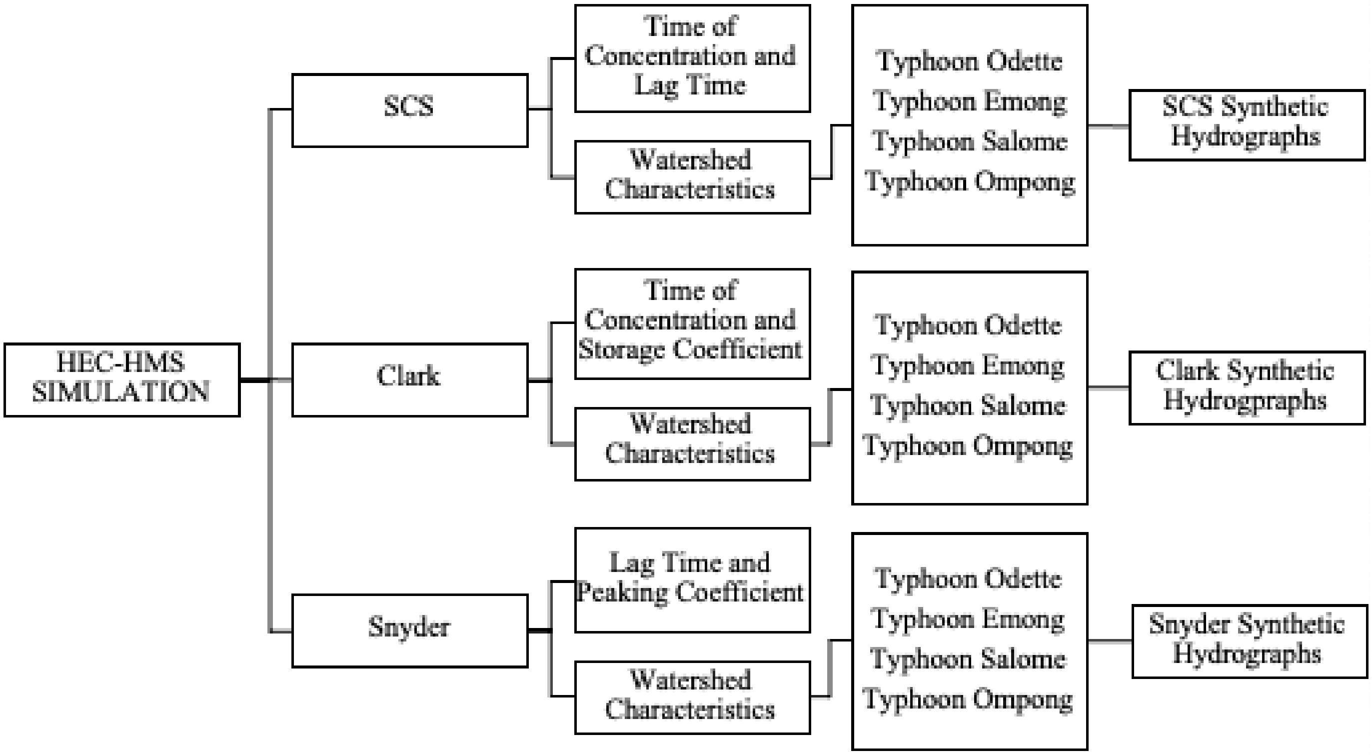

Figure 1. Simulation process in HEC-HMS using SCS, Clark, and Snyder's Unit Hydrographs to generate the hydrographs for Makiling Forest Reserve.

Hydrologic Model Parameter Testing

The calibrated hydrographs for each runoff modeling technique were compared to the actual hydrographs at the gauged watershed. The comparison was made using the three hydrologic model parameters: Nash-Sutcliffe Efficiency (NSE), Index of Volumetric Fit (IVF), and Relative Error of Peak Flow (REP). Formulas for these hydrologic parameters are shown in Equations 8, 9, 10.

$$NSE = 1 - \frac{\sum[(Q_o)_t - (Q_s)_t]^2}{\sum[(Q_o)_t - Q_{ave}]^2} \tag{8}$$

where:
NSE is the value for the Nash-Sutcliffe Efficiency
$(Q_o)_t$ is the actual discharge at time *t* in $m^3\ s^{-1}$
$(Q_s)_t$ is the simulated discharge at time *t* in $m^3\ s^{-1}$
Q_{ave} is the average of the actual discharge data for a specific time frame in m^3/s

$$IVF = \frac{\sum(Q_s)_t}{\sum(Q_0)_t} \tag{9}$$

where:
IVF is the value for the Index of Volumetric Flow
$(Q_s)_t$ is the observed discharge data at time *t* in $m^3\ s^{-1}$
$(Q_0)_t$ is the simulated discharge at time *t* in $m^3\ s^{-1}$

$$REP = \frac{|(Q_p)_s - (Q_p)_o|}{(Q_p)_o} \tag{10}$$

where:
REP is the value for the Relative Error of Peak Flow
$(Q_p)_s$ is the peak flow in the simulation in $m^3\ s^{-1}$
$(Q_p)_o$ is the actual peak flow in $m^3\ s^{-1}$

NSE coefficient is used to evaluate how a given hydrological model correctly predicts the actual streamflow discharge (*Amin et al. 2017*). The performance of the synthetic UH is classified depending on the NSE values ($NSE \leq 0.50$: Unsatisfactory; $0.50 < NSE \leq 0.65$: Satisfactory; $0.65 < NSE \leq 0.75$: Good; $0.75 < NSE \leq 1.00$: Very good) (*Moriasi et al. 2007*). An NSE value equal to one means that the hydrologic model perfectly fits the actual discharge data (*Lin et al. 2017*). IVF is used to determine the ratio of the total volumes of the simulated and the actual discharge values (*Xiong and O'connor 2002*). This is an essential test of accuracy since the total water volume of runoff is one of the most important information in modeling that can be extracted from a hydrograph (*Wambura et al. 2018*). The REP measures the performance of the peak flow of a synthetic hydrograph in comparison with the actual hydrograph. This hydrologic model parameter is essential in estimating how a certain storm event behaves, specifically its potential to attain the maximum amount of discharge. A REP value of zero means that the peak flow of the simulated hydrograph and the actual hydrograph is equal (*Barco et al. 2008*).

The runoff modeling technique which best fits the actual hydrograph and acquired an acceptable value for each hydrologic model parameter for each storm event will be used for the neighboring ungauged watersheds in the MFR.

Development of Runoff Model for the Ungauged Watersheds

The spatial proximity regionalization (SPR) technique was utilized for the development of synthetic hydrographs for the ungauged watershed. In this method, the known or calibrated watershed parameters of a gauged watershed are adopted and utilized for the neighboring ungauged watersheds in the assumption that these watersheds and the gauged watersheds have the same climatic and physical characteristics due to proximity (*Oudin et al. 2008*). Using the rainfall depth values from the RIDF of the NAS in UPLB, the synthetic hydrographs for different return periods (2-, 5-, 10-, 15-, 20-, 25-, 50-, 100-yr) of the neighboring watersheds were generated.

Gauged Watershed Characterization

The gauged Molawin Watershed was delineated by setting the location of the gauging instrument (14.15834°N, 121.23150°E) (**Figure 2**). It was then divided into sub-watershed and the channels in each were extended up to the highest point to determine the longest flow length. The characteristics of each watershed includes the longest flow length and the average slope of each sub-watershed (**Table 2**).

The soil texture of the Molawin Watershed was acquired from the Soil Series Map of the MFR created by the *Makiling Center for Mountain Ecosystem* (*2010*). The Soil series map was geo-referenced in QGIS 2.18 to be able to layer the sub-watersheds on top of the soil series map.

Table 2. Characteristics of each sub-watershed of the Molawin Watershed.

Sub-watershed	Area (km^2)	Longest flow length of river (m)	Average slope (%)
S100	1.369	2,912.7	9.50
S110	1.148	3,053.3	10.10
S120	1.072	2,533.2	8.10
S130	1.057	2,561.9	9.90

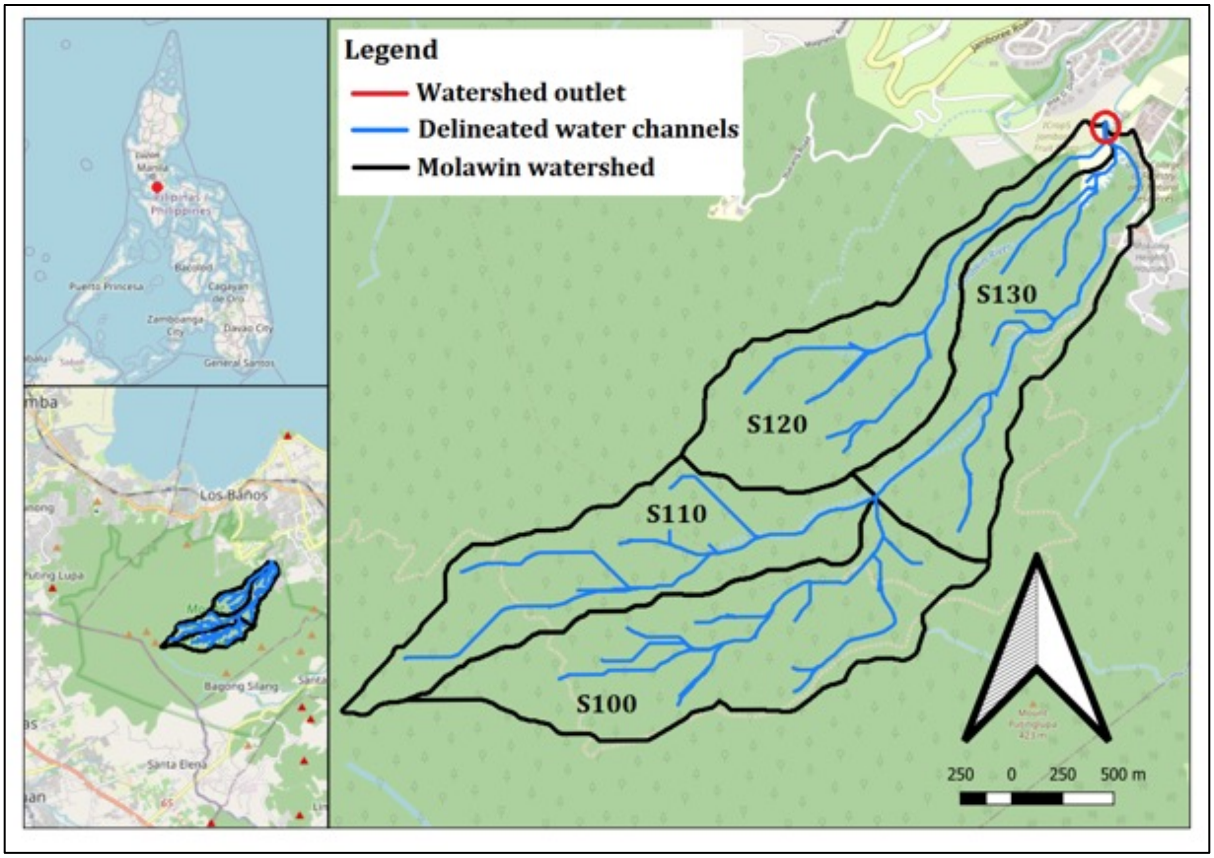

Figure 2. The gauged Molawin Watershed in the Makiling Forest Reserve, Laguna, Philippines delineated into Sub-watersheds.

RESULTS AND DISCUSSIONS

All sub-watersheds were found to have a soil texture of Macolod clay loam, which belongs to hydrologic soil group D (highest runoff potential) under the SCS classification.

The MFR is composed mostly of closed and open forests with broadleaved trees. Cover types such as cultivated lands, natural land, and grasslands were also observed. The Land Cover Map was geo-referenced in QGIS 2.18 and superimposed with the sub-watersheds to determine the land cover classification of each sub-watershed (**Table 3**).

Using the acquired land cover data, the respective runoff curve numbers (CN) of each sub-watershed were identified using the CN Table indicated in the Technical Release No. 55 (TR-55) of the USDA-NRCS. The CN value estimates the rainfall excess during a certain precipitation event (*Halwatura and Najim 2013*). Except for sub-watersheds S120-3a and S130-4a, which obtained a CN of 77, the rest have a CN value of 79. With two different CN values, the weighted CN for sub-watersheds S120 and S130 were calculated to be 78.935 and 78.807, respectively. Other watershed parameters needed for the simulations such as initial abstraction and potential maximum retention are computed based depend on the CN values. Only sub-watersheds S120 and S130 obtained

Table 3. Land cover classification of the Molawin sub-watersheds.

Sub-watershed	Divide	Land Cover Type
S100	1a	Closed Forest - broadleaved
	1b	Open Forest - broadleaved
S110	2a	Closed Forest - broadleaved
	2b	Open Forest - broadleaved
S120	3a	Other land, cultivated, perennial crop
	3b	Open Forest - broadleaved
S130	4a	Other land, cultivated, perennial crop
	4b	Open Forest - broadleaved

values for the impervious area since these are located in the lower area of the MFR which includes UPLB.

Initial Simulation Parameters

Given the different derived and actual watershed properties like CN, average slope, longest river flow length data, watershed coefficient, and length of the stream from the outlet to the point nearest to the centroid (**Table 4**), the values of time of concentration (T_c), lag time (T_L), and storage coefficient (R), for the SCS, Clark, and Snyder UH were computed using HEC-HMS (**Table 5**). The value for the peaking coefficient of the watershed was assumed to be equal to 0.4 for all sub-watershed since the MFR is considered a mountainous site.

Runoff Model Simulations and Calibration

The rainfall depths for the four storm events were transformed using Horton's equation and used as the input hyetograph for the simulations. The basin model of the gauged Molawin Watershed was generated in HEC-HMS. The actual hydrographs measured at the MFR gauging station from the four storms were compared with the synthetic hydrographs generated using SCS, Clark, and Snyder's UH methods (**Figure 3**).

Three hydrologic model parameter tests, the Nash-Sutcliffe Efficiency (NSE), Index of Volumetric Fit (IVF), and Relative Error of Peak Flow (REP), were used to determine which runoff modeling technique best fits the site (**Table 6**).

Visual inspection showed that the synthetic hydrographs simulated using Snyder's UH are better fit to the actual hydrographs (**Figure 3**). However, based on the computed NSE values, only Snyder's calibrated UH on Typhoon Ompong (3a on **Figure 3**) with NSE = 0.664 can be considered as a "good" fit. Except for Clark UH result on Typhoon Ompong, which is considered Satisfactory, all the other synthetic UH on all storms are unsatisfactory using the NSE test.

An IVF value of 1.0 means that the simulated hydrograph perfectly fits the actual hydrograph (*Tibebe et al. 2013*). Based on the average IVF values for each runoff modeling technique (**Table 6**), Snyder's UH showed the least deviation (0.06), from the recommended IVF value (1.0). Clark's UH also showed the same difference, 0.06, while SCS got 0.09, but both are negative which means that the total runoff volumes of the simulation are less than that of the actual, underestimating the volume of flow from the storm.

In the analysis of the performance of the runoff models using REP values for each storm, Clark UH generated the best fit with a REP value of zero on its simulation of Typhoon Emong, but at the same time, generated the worst fit with a REP of 1.62 for Typhoon Salome. The SCS UH obtained a good fit for Typhoons Emong and Salome with REP values of 0.06 and 0.08, respectively. Snyder's UH achieved a good fit for Typhoons Ompong and Emong with REP values of 0.08 and 0.10, respectively. On average, SCS UH and Snyder's UH showed better fit using the REP model parameter test.

Overall, Snyder's UH simulations best describe the four storm events based on the obtained values of the three hydrologic model parameters. Thus, Snyder's UH was used as the runoff modeling technique for

Table 4. Initial parameters and watershed properties of each sub-watershed.

Sub-watershed	Curve Number	Slope (m/m)	Longest Flow of Length of River (m)	Centroid to Outlet Length (km)	Peaking Coefficient	Area (km^2)
S100	79.000	0.095	2912.69	1.141	0.4	1.369
S110	79.000	0.101	3053.26	1.229	0.4	1.148
S120	78.935	0.810	2988.80	1.721	0.4	1.072
S130	78.807	0.099	2561.89	1.325	0.4	1.057

Table 5. Computed values for the time of concentration (T_c), storage coefficient (R), and lag time (T_L) using HEC-HMS for each runoff modeling technique.

Sub-watershed	T_c		R	T_L	
	SCS (h)	Clark (min)	Clark	SCS (h)	Snyder (h)
S100	22.226	38.008	27.677	13.336	2.151
S110	23.010	34.652	25.233	13.806	2.230
S120	20.440	34.069	24.808	12.264	2.333
S130	20.180	30.860	22.471	12.108	2.164

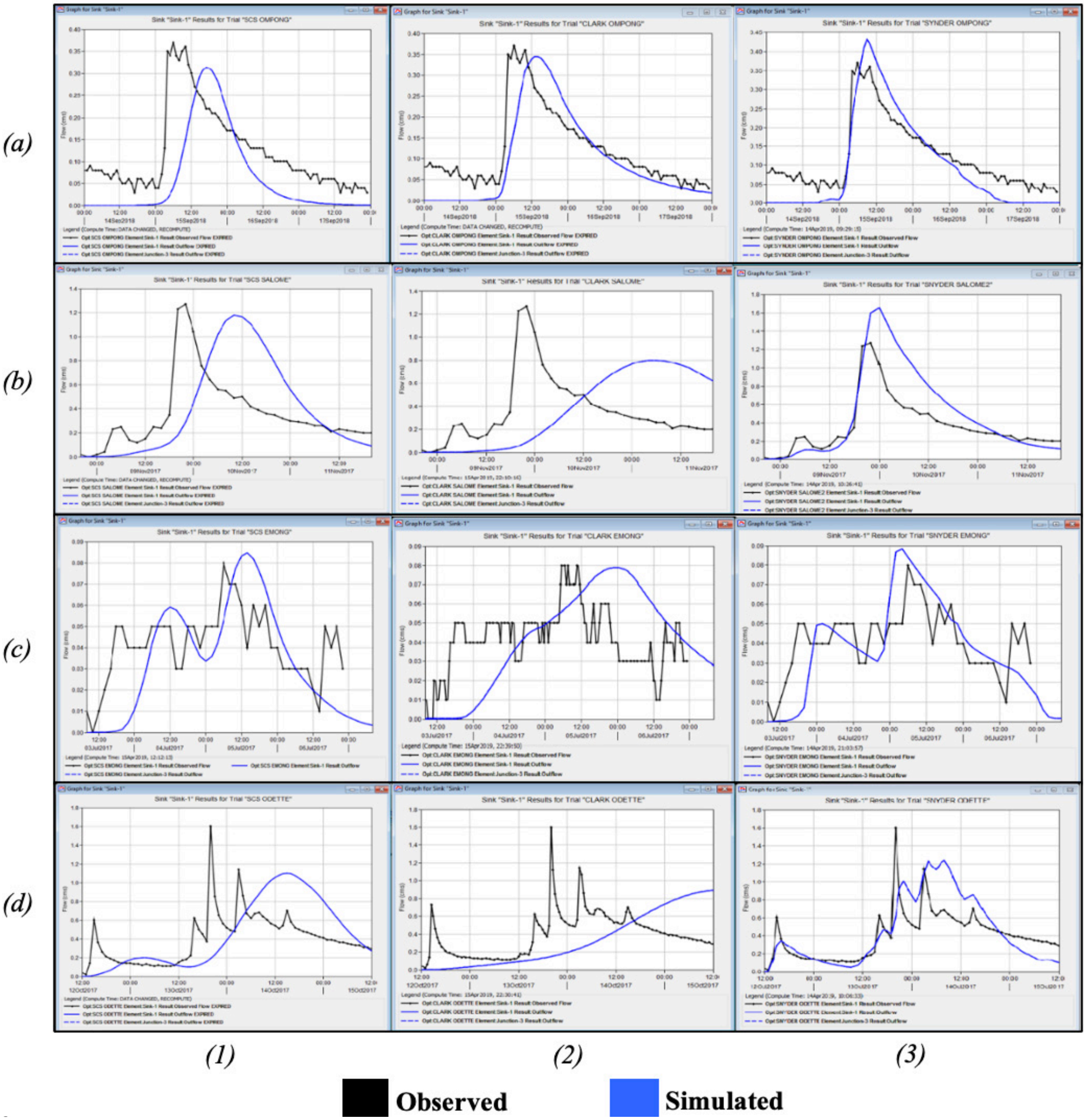

Figure 3. Actual and simulated hydrographs for (a) Typhoon Ompong, (b) Salome, (c) Emong, (d) Odette using (1) SCS, (2) Clark, and (3) Snyder's Unit Hydrograph.

the development of the hydrographs of the ungauged watersheds of the MFR at different return periods.

Regionalization of the Ungauged Watersheds

Using the spatial proximity regionalization technique, the weighted average values of the calibrated watershed parameters curve number, initial abstraction, and peaking coefficient were calculated to be 54.75, 0.27, and 0.18, respectively. Since SPR is limited to watersheds that exhibit the same climatic and physical characteristics, three ungauged watersheds in the MFR namely Tigbi, Dampalit, and Cambantoc, were considered (**Figure 4**). The watershed characteristics for each ungauged watershed were based on the data requirements of Snyder's UH (**Table 7**).

Table 6. Nash-Sutcliffe Efficiency (NSE), Index of Volumetric Fit (IVF), and Relative Error of Peak Flow (REP) values for each runoff modelling technique.

Typhoon	**Nash-Sutcliff Efficiency**		
	SCS UH	**Clark UH**	**Snyder's UH**
Odette	-0.649	-1.022	0.122
Emong	-0.713	-1.757	-0.124
Salome	-0.795	-1.425	0.188
Ompong	-0.16	0.510	0.664
Typhoon	**Index of Volumetric Flow**		
	SCS UH	**Clark UH**	**Snyder's UH**
Odette	1.12	0.82	1.12
Emong	0.89	1.10	0.99
Salome	1.10	1.02	1.32
Ompong	0.51	0.81	0.80
Average	0.91	0.94	1.06
Deviation	-0.09	-0.06	0.06
Typhoon	**Relative Error of Peak Flow**		
	SCS UH	**Clark UH**	**Snyder's UH**
Odette	0.31	0.44	0.25
Emong	0.06	0.00	0.10
Salome	0.08	1.62	0.31
Ompong	0.25	0.25	0.08
Average		0.58	0.19

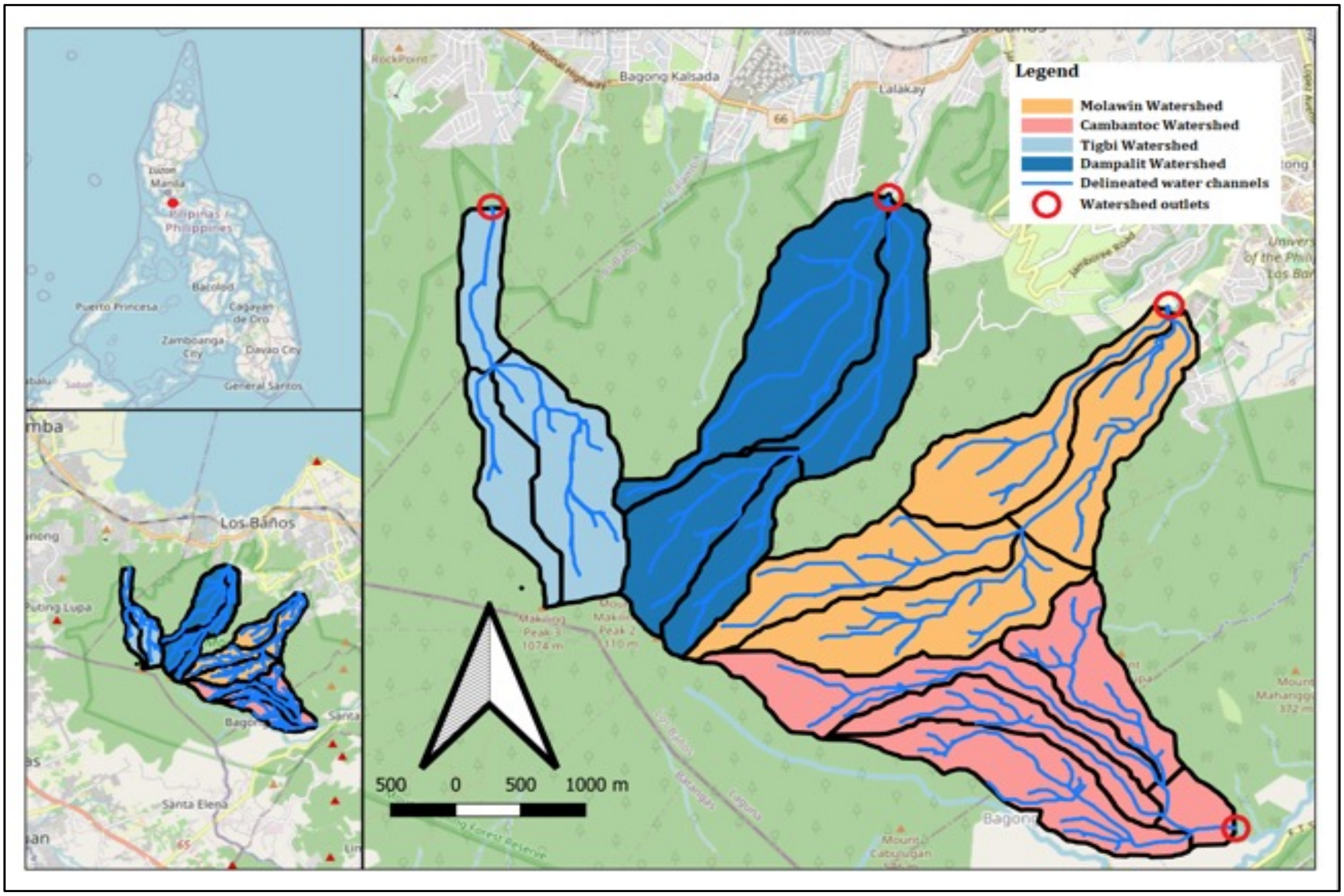

Figure 4. Delineated watersheds with similar climatic types in the Makiling Forest Reserve, Laguna, Philippines.

Table 7. Watershed characteristics of ungauged watersheds for the Makiling Forest Reserve (MFR), Laguna, Philippines.

Name of watershed	Sub-watershed	Area (km^2)	Longest flow length (km)	Centroid to outlet (km)	Lag time (hr)
Tigbi	S200	0.569	2.310	1.049	1.957
	S210	1.180	2.698	1.499	2.281
	S220	0.417	1.432	0.693	1.497
	S300	0.869	2.032	1.084	1.901
Dampalit	S310	0.544	2.081	1.168	1.958
	S320	1.829	3.748	0.831	2.109
	S330	0.993	2.537	1.540	2.258
	S400	1.053	3.399	1.422	2.407
	S410	0.695	3.182	1.610	2.449
Cambantoc	S420	1.053	4.336	2.508	3.069
	S430	0.789	2.394	1.406	2.159
	S440	0.269	0.878	0.305	1.011

Runoff Model Simulation for the Ungauged Watersheds

The basin models of the ungauged watersheds were generated in HEC-HMS. Using the respective watershed characteristics, the synthetic unit hydrographs of Tigbi, Dampalit, and Cambantoc watersheds were generated (**Figure 5**). Similar behavior of the generated synthetic hydrographs can be observed from the Tigbi, Dampalit, and Cambantoc watersheds using visual inspection. The peak flows for each synthetic hydrograph of each return period differs because there is a direct relationship between the precipitation values and the return period. Consequently, the higher the return period, the higher is the total runoff volume.

Significant progress has been made in the development of regionalization methods (*Razavi and Coulibaly 2013*). However, there is no universal method for a given region or catchment and the best approach is to test which method is the most appropriate for the given watershed and region with different watershed sizes, topography, and climate types (*Samuel et al. 2012*). This study showed that spatial proximity regionalization techniques can be applied to small ungauged watersheds in the humid tropics where strong typhoons are a common occurrence. The values of the peak flow, the total volume of runoff, and the time to peak for the Tigbi, Dampalit, and Cambantoc watersheds were summarized using the generated synthetic hydrographs for each return period (**Table 8**).

Despite several limitations, a high level of confidence is achieved in the generated synthetic hydrographs due to the calibration of the known watershed properties and validation with actual hydrographs. The results of this study are consistent with that of *Oudin et al.* (*2008*) and *Drogue and Khediri* (*2016*), which show that spatial

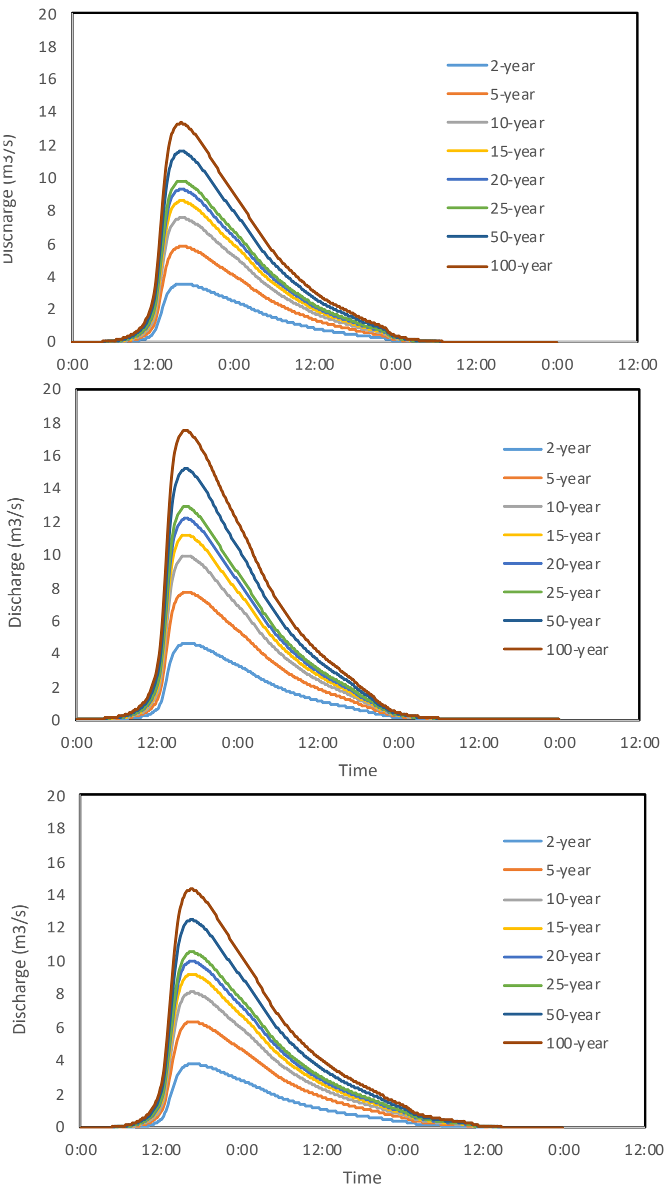

Figure 5. Synthetic hydrographs of (a) Tigbi, (b) Dampalit, and (c) Cambantoc Watersheds using Snyder's Unit Hydrograph for every return period.

Table 8. Summary of peak discharge values of each return period of Tigbi, Dampalit and Cambantoc watershed.

Return period (year)	**Tigbi Watershed**		
	Peak Flow (m^3 s)	**Total Volume of Runoff (1000 m^3)**	**Time to Peak (hr)**
2	3.5	216.0	16:30
5	5.9	359.0	16:20
10	7.6	461.7	16:20
15	8.6	521.6	16:20
20	9.3	564.6	16:20
25	9.8	597.7	16:20
50	11.6	702.6	16:20
100	13.4	809.0	16:10
Return period (year)	**Dampalit Watershed**		
	Peak Flow (m^3 s)	**Total Volume of Runoff (1000 m^3)**	**Time to Peak (hr)**
2	4.6	279.4	16:30
5	7.7	465.1	16:20
10	9.9	598.0	16:20
15	11.2	675.5	16:20
20	12.2	731.3	16:20
25	12.9	774.8	16:20
50	15.2	910.5	16:20
100	17.5	1049.0	16:10
Return period (year)	**Cambantoc Watershed**		
	Peak Flow (m^3 s)	**Total Volume of runoff (1000 m^3)**	**Time to Peak (hr)**
2	3.8	255.2	16:40
5	6.3	424.0	16:40
10	8.2	545.5	16:30
15	9.2	616.2	16:30
20	10.0	666.9	16:30
25	10.6	706.4	16:30
50	12.5	829.9	16:30
100	14.4	955.7	16:30

proximity is the best regionalization method compared to linear regression or physical similarity and that it works best for ungauged watersheds with similar hydro-meteorological and physical conditions. For instance, *Clanor et al.* (*2016*) suggest that for ungauged watersheds in the Philippines, the method of spatial proximity regionalization is still a better option as long as proper regionalization techniques are employed.

CONCLUSION

In this study, synthetic unit hydrographs were generated using three runoff modeling techniques and then calibrated using actual streamflow data from four storm events. Snyder's UH acquired the best results for the four storm events. The weighted average values of the calibrated watershed parameters from the Snyder's UH were calculated using the spatial proximity regionalization technique and used as input values to generate the synthetic hydrographs at different return periods for three ungauged watersheds in the Makiling Forest Reserve.

In the absence of actual streamflow data, the spatial proximity regionalization method can be used to determine the weighted watershed parameters from synthetic hydrographs of gauged watersheds and used to generate synthetic hydrographs of neighboring ungauged watersheds. By modeling and calibrating watershed characteristics based on the actual data of the gauged watershed, this method enables a more accurate estimation of the volume of runoff, the magnitude of peak flow, and the time to peak for different storm return periods which are valuable data needed in watershed planning, water resources management, flood forecasting, and design of water control structures.

For future developments of the study, the change in the value of the runoff curve numbers can be assessed by considering the historical changes in the land cover, soil type, and other physical parameters of the MFR. Other research suggests that combining various models of approach could acquire more favorable results based on the studies by *Samuel et al.* (*2012*), *Lebecherel et al. 2016,* and *Li et al.* (*2019*). Further, other applications may be used in producing the synthetic hydrographs of ungauged watersheds (GR4J, WASMOD, HBV, and XAJ) provided that data for these models are available (*Yang et al. 2020*).

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