Exponent determination in a poorly gauged basin system in Nigeria based on flow characteristics investigation and regionalization method

O. A. Fasipe¹ · O. C. Izinyon²

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Abstract

In this study, a method for estimating the exponent “ n ” values of the catchment-area equations of four sub-basins within the poorly gauged Benin-Owena River Basin Development Authority (BORBDA) in Nigeria is presented to enable the estimation of flows at ungauged sites within the basin and the determination of small hydropower (SHP) potential at different locations in each sub-basin and the entire basin. Optimal prediction of streamflow characteristics in poorly gauged basin requires developing a methodology for extrapolation of data from gauged to ungauged sites within the basin. Four sub-catchments of BORBDA, a poorly gauged basin in Nigeria, were investigated using Remote Sensing (RS), Geographic Information System (GIS), statistical techniques, and Natural Resources Conservation Service–Curve Number (NRCS-CN) hydrological model. Discharge values at gauged sites (Q_g) were obtained from recorded discharge values collected for 12 months at an established gauging station in each sub-basin. RS and GIS techniques were used to develop classification maps and obtain crucial data like curve number (CN), elevation, Hydrologic Soil Group (HSG), rainfall intensity, slope, area of gauged and ungauged required for evaluating spatial discharge (ungauged) utilizing NRCS-CN model. From the established model for each sub-basin, exponent “ n ” in the relationship between discharge and catchment area was obtained to be 0.23, 0.41, 0.71, and 0.74. Using the lumped modeling approach, which considers a watershed as a single unit for computation, where watershed parameters and variables were to be averaged produced “ n ” = 0.52 for BORBDA area, which is within the range of 0.5–0.85 suggested by previous researchers. Obtained BORBDA exponent “ n ” was validated for use in the entire basin through soil homogeneity test by generating BORBDA soil map which confirms the four sub-basins investigated share similar HSG A, B, and D with BORBDA. The exponent “ n ” value is useful for predicting flows in ungauged parts of the basin. The exponent “ n ” value obtained for the basin is helpful in the assessment of discharge and determination of SHP potential at different locations within the poorly gauged BORBDA basin, and the dissemination of the research findings will find practical use and guide to practicing hydrologists in Nigeria and locations around the world with similar challenges of poorly gauged basins particularly Africa and other developing countries.

Keywords GIS · RS · Exponent “ n ” · SHP · Ungauged basin · Gauge basin · Discharge · NRCS-CN model

1 Introduction

The physical characteristics of catchment play a significant role in the hydrological response of the catchment. To comprehend the laws of runoff processes in a watershed,

hydrologists are confronted with numerous problems, particularly with regard to ungauged catchment, where hydrological data are not readily available and accessible [1].

✉ O. A. Fasipe, fasipeo@gmail.com; O. C. Izinyon, izinyon@uniben.edu | ¹Energy Commission of Nigeria, Abuja, Nigeria. ²Department of Civil Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria.

The lack of adequate hydrological data is caused by myriad of reasons; for example, poorly gauged river basins, low density of hydrological gauging stations, breakdown and lack of gauging equipment, inadequate trained manpower, vandalization of gauging instruments, insufficient funding for the sector, inaccessible sites, etc., present serious challenge to sustainable water resources planning, design, and management in developing countries including Nigeria. This has led to short length or non-continuous records hence rendering collected data unsuitable for long-term planning.

The demand for useful hydrological data in Sub-Saharan Africa (SSA) is growing, while specialized and individual competencies are decreasing, as confirmed by decrease in quantity of Africa's meteorological stations over the last 30 years [2, 3]. Nigeria is divided into eight hydrological

areas (HA) objectively for water resources management, taking into account topographical and hydrological conditions (Fig. 1) [4], and they are either ungauged or poorly gauged, resulting in observed data not being adequate for efficient water resources planning and development. The absence of statistics regarding the amount and condition of water resources potential in a basin gives rise to unproductive hydrological networks. World Meteorological Organization (WMO) guideline stated that the expected number of rain gauges to reduce cost and boost proficiency for clement Mediterranean and flat tropical region is in the scope of 600–900 km² per gauge. The effect of not expanding Nigeria's existing rain gauges is a 10% upsurge in error of any result based on the existing 87 gauges [5] as against 1074 ideal number of rain gauges recognized by [6] for Nigeria using WMO Standard.

Fig. 1 Nigeria map showing the eight hydrological areas [4]

Besides, [7] stated that between 10 and 30 years time frame would be required before satisfactory statistics or data can be assembled for predicting the hydrological regimes of rivers if adequate financial resources were available for expansion of hydrometric networks. Consequently, problem of inadequate hydrological data is expected to persist over a long time in Africa and Nigeria included. Therefore, there is need to exploit other means of predicting flow characteristics at ungauged or poorly gauged sites to engender optimal catchment harnessing plan by extrapolating or transferring data from gauged to ungauged sites, a process called regionalization [8]. However, watershed regionalization is of two types [9]: regionalization based on catchment attributes as presented in [10–12] and regionalization based on spatial proximity as reviewed in [16–22]. This paper's regionalization method is that of the former, which involves the formulation of an observational relationship between discharge and catchment-area characteristics explicitly [13, 14].

[11] stated that due to the inability to gauge all rivers in a country as a result of financial and terrain constraints, streamflow data at a target site might not be available, hence the need to introduce and take advantage of regionalization to solve water resources management challenges. [12] consider the estimation of discharge at an ungauged site by combining data from modern-day data loggers with gauged site information to develop a stage–discharge relationship to estimate discharge. [15] underscored the importance of discharge estimation at ungauged sites to solve data scarcity challenges in hydrological catchment by listing some criteria to be considered when carrying out an evaluation, which includes geographic, hydrogeologic, and size similarities.

[16] carried out watershed regionalization using the rough set concept in Iran Sefidrud basin. Their results show that the proposed algorithm outperforms the common clustering algorithm used for regionalization in terms of the number of watersheds assigned to homogeneous regions. [17] developed some algorithms using cluster analysis for regionalization that can be applied to feature vectors consisting of watershed features comparably in gauged and ungauged catchments simultaneously to assess the effect of merging flood statistics in Iran Karun-e-Bozorg basin. The outcomes demonstrate that the combination of flood statistics with a suitable weight to the feature vectors utilized in regionalization might enhance regionalization performance consistent with the number of catchments allocated to the homogeneous regions. Similarly, the proposed regionalization procedures can grow the number of watersheds allocated to the homogeneous regions distinctively. [18] applied in the south-west Karun-e-Bozorg basin of Iran Gaussian mixture models for regionalization of catchments and examine

finite mixture models' performance in watershed regionalization compared to hybrid clustering algorithms. The results show that the Gaussian mixture models outperformed the hybrid clustering algorithm in recognizing homogeneous regions. They concluded generally based on their research's evidence that finite mixture models can be considered a capable choice for the regionalization of catchments in regional flood frequency analysis studies. [19] evaluated the developed algorithm's performance to select catchment features for regionalization using Monte Carlo simulation testing in the Karun-e-Bozorg basin. They conclude on the strength of their results that the algorithm efficiency increases by growing the number of obtainable watershed characteristics. [20] utilized the advantages of two regionalization techniques, namely cluster analysis and canonical correlation analysis in Iran's Sefidrud basin. The performance evaluation method indicates that all the methods proposed can provide good regionalization options to improve regions homogeneity. Results obtained show the technique can fulfill the homogeneity conditions for all the regions identified in the study area. [21] explore the method of the nearest and farthest neighbor data points to identify relevant features using criteria such as Spearman's rank correlation coefficient and mutual information criterion needed for watershed regionalization by relating catchment features to flood data records to improve regions homogeneity. The study identified drainage area, longitude, and runoff coefficient as prominent characteristics in Sefidrud basin regionalization utilizing the best choice of five farthest and five nearest. The outcomes confirm that for regional flood frequency analysis, the proposed method can be regarded as an effective means for creating homogeneous regions. [22] stressed the importance of studying satellite data precision using ERA5, PERSIANN-CCS, and TRMM datasets in Iran (Idenak region) between 2003 and 2014. Their study results show that the monthly and annual rainfall data derived from TRMM and ERA5 model fits obtained rainfall data spatial distribution and observational data correspondingly. ERA5 model has better detection capabilities in all the stations considered except Ghale-Raeesi, where PERSIANN-CCS shows higher ability.

As Nigeria targets generation of 2GW by 2025 from SHP resources [23] and electric power supply from the National grid is epileptic, resulting in low access to power supply especially in rural communities causing low electric power consumption per capita of only 150 kWh compared to South Africa with 3,904 kWh in 2016. Harnessing SHP resources present feasible options to improve energy supply across the river basins in Nigeria because of the enormous SHP potential of river systems in Nigeria, which has been put at about 3.5GW, of which only 2% has been tapped thus far. The main contribution to

the slow utilization, development, and diffusion of SHP technologies despite the high potential is mainly due to unreliable hydrological and SHP database with up-to-date information on potential sites across the country, which can assist in attracting investments. Consequently, this research applied Remote Sensing (RS), Geographic Information System (GIS), and Natural Resources Conservation Service-Curve Number (NRCS-CN) hydrological model with a view of solving the perennial problem of data scarcity by obtaining flow characteristics of poorly gauged Okhunwan, Oyanmi, Owan, and Osse sub-basins which will assist in determination of exponent "n" of the regionalization equation that can be used in predicting membership of other neighboring ungauged sub-basins around the studied sites and further enhance simplification of hydropower potential determination of ungauged rivers in the basin.

In recent times, RS and GIS procedures have been successfully utilized as reliable tools in deciding the quantifiable variety of the catchment geometry and change in land use–land cover (LULC) in Devak catchment up to Gura Slathian in Jammu region of Jammu and Kashmir (J&K), India. The research results form a valuable template for estimating, interpreting, and investigating hydrological catchment characteristics with significant contributions to different hydrological models [1]. For instance, Digital Elevation Models (DEMs) are employed to define catchments characteristics [24], examine drainage networks, and forecast soil water attributes [25], as well as execute hydrograph assessment [26]. [27] utilized Earth Observation (EO) technology data to manage water resources across African countries, focusing on overcoming difficulties encountered during the gathering, analysis, and dissemination of water-related geo-information. The study results demonstrate EO technologies' capabilities to obtained catchment characteristics data such as LULC and geology, the formation of inventories and evaluation of flooding patterns, management and analysis of large aquifers using decision-support systems or models. [28] explore the application of RS satellite data to size, site, and evaluate micro-hydropower potential in Nepal by including of impact of topography (hillslope) in infrastructure layout, discharge variability constraints, and local electricity demand of the plants. The procedure performance was matched against 148 existing sites, which indicates its ability to predict an excellent location for hydropower development correctly but unable to reproduce specific design characteristics.

This paper utilized GIS and RS to derive catchment physical characteristics, i.e., elevation, rainfall, soil, slope, LULC, and curve number (CN), useful in computation of discharge characteristics of poorly gauged catchments, while the spatial discharge (point to point differences in discharge volumes taking into consideration spatial

changes in physiographic features) was computed via NRCS-CN hydrological model. The method utilized in this study is encouraged for wide application in hydrologically data scarce country like Nigeria and regions such as SSA, Africa in general, and beyond. This study is limited to the application of RS, GIS, and NRCS-CN rainfall–runoff model to evaluate flow characteristics in a poorly gauged basin in Nigeria. Catchment-area ratio method relates discharge capabilities; area of gauged and ungauged sites was utilized to carry out regionalization [10–12]. As discussed by [10], other regionalization techniques such as the regional flow duration curve method can be explored for research on the present BORB to reinforce the inferences represented by this investigation.

2 Study area

The study area is the Benin-Owena River Basin (BORB) catchment area situated within Western Littoral Hydrological Area HA-6, one of the eight hydrological areas into which Nigeria is subdivided. The BORB comprises of several sub-basins, and four of these sub-basins, namely Okhunwan, Oyanmi, Owan, and Osse, form the nucleus of this study because they have archival data ranging from six to eleven years that can be relied upon to predict the hydrological regimes of selected rivers. The BORB hydrological network covers an area of 45,950.06 Sq Km in the territories of Edo, Ekiti, Ondo states, and Delta North Senatorial District in Delta state. The basin area falls within 5° 22' 0" and 8° 0' 0" North Latitude and 4° 19' 0" and 6° 40' 0" East Longitude. Two major seasons occur in this area, viz the dry season (November to March) and the stormy or wet season (April to October). Maximum temperatures range between 30 and 35 °C during dry periods and 21–26 °C during the wet periods. The mean annual precipitation over the area ranges from 1600 to 3000 mm. Also, the annual evapotranspiration ranges from about 800 to 1200 mm, and the runoff from 400 to 2000 mm [29].

The Hydrological Area shares a boundary to the North with Kwara and Kogi states and on the East coast with River Niger, while west, it shares common boundary with Osun and Ogun States and to the south, the Atlantic Ocean borders it. The terrain varies from being partially flat in the south and partly hilly in the North, while the vegetation varies from Mangrove Swamp to Tropical Forest. The highest elevation is about 400 m above sea level, and the lowest corresponds to sea level. Most of the rivers flow from North to South to the Bight of Benin except for a few tributaries of the Niger River [29], as presented in Fig. 2.

The steps followed to determine the exponent " n " in the catchment-area ratio model for the BORB area are as presented in the flowchart given in Fig. 3.

Four sub-basins of the BORB Catchment is the focus of the present study. They are Okhunwan, Oyanmi, Owan, and Osse sub-basins. As the last available observed discharged data in the four sub-basins were recorded in year 2000,

The particulars of the four established gauging stations at which field measurements were made in 2018 are presented in Table 1.

Fig. 3 Methodology flowchart for determination of exponent "n." **Table 1** Particulars of the temporary established hydrological gauging stations for 2018 field measurements

S/N	Location of gauging station	State	Area	Latitude	Longitude	Sub-basin drainage area Km ²
1	Okhunwan River at Abunwa	Edo	Abunwa	6° 26' 47.075" N	5° 54' 19.775" E	195.75
2	Oyanmi River at Oloma	Edo	Oloma	7° 16' 0.578" N	6° 3' 18.757" E	529.04
3	Owan River at Sabongida	Edo	Sabongida	6° 54' 19.695" N	5° 56' 7.497" E	1216.50
4	Osse River at Isewe	Ondo	Isewe	7° 3' 25.529" N	5° 36' 49.097" E	2248.94

Source: RS, GIS and Fieldwork

The monthly average discharge measurements obtained at the gauging stations were compared with simulated data using NRCS-CN method by Pearson's product-moment correlation statistical approach at 0.05 level of confidence to determine the statistical significance of the obtained results.

3.2 Identification of catchment characteristics used for predicting flow characteristics of ungauged catchments.

As the streams in the BORB catchment are poorly gauged or ungauged, geomorphological parameters of the basin

Table 2 NIMET synoptic rainfall stations

S/N	Sub-basin	State	Synoptic station
1	Okhunwan sub-basin	Edo	Benin
2	Oyanmi sub-basin	Kogi	Lokoja
3	Owan sub-basin	Edo	Benin
4	Osse sub-basin	Ondo	Akure

offer a choice to determine relationships describing flow process of the watershed. Various physical characteristics such as slope, elevation of each sub-catchment are evaluated in this research. The obtained parameters were used to test the NRCS-CN hydrological model.

3.2.1 Rainfall data acquisition

The data were sourced from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR). PERSIANN-CDR is a Climate Data Record, which the National Research Council (NRC) describes as a time series of estimates of adequate length, reliability, and coherence to establish climate adaptability and change [30]. Measured rainfall data from the synoptic stations close to the study area were collected for the year 2018, as given in Table 2. These data were obtained from the Nigeria Meteorological Agency (NIMET), Oshodi, Lagos State. However, in order to achieve a spatial coverage of rainfall events, precipitation events were simulated for other portions of each sub-basins using RS and GIS approach. To achieve this, gridded rainfall data of year 2018 (January–December) were acquired from PERSIANN-CDR; the data covers a spatial extent of 0.25×0.25 degrees (covering the sub-basins of interest), using *Raster Calculator* in ArcMap.

3.2.2 Generation of LULC map

Land use (LU) implies the manner by which land has been utilized by people and their environment, generally with importance on the efficient function of land for economic activities. Land cover (LC) denotes physical features of earth's surface, described in the allotment of soil, water, vegetation, and other physical qualities of the land, including those made exclusively by human activities, e.g., settlements [31]. LULC map was generated for the purpose of classifying the watershed based on physical activities and features. The land-use map was produced using the Landsat 8 Imagery adopting the following steps;

- Landsat image was imported into ArcMap environment
- The image was clipped with the generated watershed boundary extent using the *Clip raster tool*

- The clipped data were confirmed to match spatially with the watershed boundary by means of visualization
- A supervised classification was carried out on the clipped image using the image analysis tool of ArcMap to achieve the study area land-use map.

3.2.3 Slope/elevation from DEM

The elevation raster was generated from the DEM using the create elevation tool. Also, slope classes were generated using Slope tool in Spatial Analyst toolbox. The Shuttle Radar Topography Mission (SRTM) DEM data used for this study was downloaded from the earth explorer website (<http://earthexplorer.usgs.gov/>). This DEM had a 30-m spatial resolution. The SRTM DEM data were used in computing slope and elevation for the study area.

3.2.4 Curve number (CN) estimation

To determine the CN, basin characteristics such as information on LULC, hydrological soil type, and ground surface condition were first generated using RS and GIS method. These data were integrated into a GIS environment for a quick and accurate estimation of the runoff curve number for the basins, which is a function of the data acquired via Remote Sensing.

3.2.5 Soil texture determination

As there is no soil database for Edo and Ondo states, the Harmonized World Soil Database (HWSD) was used. The HWSD was utilized to create the generalized soil texture attribute for the various watershed boundaries; the soil raster data were added to ArcMap, using the *clip tool*; the data were clipped to the watershed boundary, and each soil case is visualized using the right symbol. Upon determination of the soil textures in each sub-basin, Table 3 showing Hydrologic Soil Group (HSG) based on USDA soil classification was used to identify the HSG of the study area.

3.2.5.1 Processing of soil data The soil data processing was achieved since soil map is available as an *ArcGIS*

Table 3 HSG based on USDA soil classification [32]

HSG	Soil texture
A	Loamy sand, sandy loam, or sand
B	Loam or silt
C	Sandy clay loam
D	Sandy clay, silty clay, clay, silt clay loam, or clay loam

shapefile, and the attribute data are available in *Microsoft Access*. So that the used layers are in the same geographic coordinate system and datum, the soil map was re-projected into the spatial reference WGS84 UTM Zone 31 N and datum WGS 1984.

3.3 Estimation of streamflow for ungauged parts of BORBDA sub-basins using the NRCS-CN Model

In this study, runoff was estimated using NRCS-CN model, and the Least Square method was used to find runoff depth (Eq. 1) [33]:

$$Q_d = \frac{[P - 0.2S]^2}{P + 0.8S} \quad (1)$$

where P is the precipitation (mm) obtained from PERSIANN-CDR in the sub-basins of Okhunwan, Oyanmi, Owan, and Osse, and S is the potential maximum retention after beginning of the runoff (mm) and is defined by Eq. (2) [34] as

$$s = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (2)$$

The peak discharge Q_p for each stream was calculated on yearly and monthly bases using the NRCS-CN method presented in [33] as

$$Q_p = \frac{2.083 * A * Q_d}{t_p} \quad (3)$$

where A is the drainage basin area (km^2), Q_d is the depth of excess rainfall (mm) obtained from Eq. 1, Q_p is unit hydrograph peak runoff rate (m^3/s), t_p is unit hydrograph time to peak runoff (hr). In the relation stated in Eq. 3, the only unknown parameter is time to peak t_p . This can be evaluated with respect to time of concentration t_c . The relationship between t_p and t_c is shown in Eq. 4:

According to [35],

$$\text{NRCS}t_p = 0.6t_c \quad (4)$$

To compute t_c value, [36] developed this empirical Eq. 5:

$$t_c = 0.0526 \left[\left(\frac{1000}{CN} \right) - 9 \right] L^{0.8} S^{-0.5} \quad (5)$$

where t_c is time of concentration (hr); CN = curve number; L = flow length (ft); S = average watershed slope (%), which is equal to H/L , where H is change in elevation between the most remote part in the watershed and the outlet.

Parameters needed for estimating time of concentration were obtained from the topographic maps. So, after

calculating t_c , t_p can simply be computed, and subsequently, the peak runoff rate Q_p .

3.4 Catchment-area ratio model

Generally, regionalization procedure depends on transferring or extrapolating data from gauged to ungauged sites. However, regionalization of a watershed or catchment can be achieved in two ways based on the research objectives. The first approach is regionalization of hydrometric zones, which recognizes regions with similar attribute to facilitate the comparison of hydrological effects such as duration of specific flow periods, occurrence and magnitude of high and low-flow events in comparable sized catchments, unit runoff from the catchment area, and average monthly flow distribution [11]. The other approach to regionalization refers to a method of identifying homogeneous regions by pooling flood data from various watersheds similar to the catchment site under investigation in terms of flood yielding mechanisms. A cluster of watersheds with proven and adequate uniformity in flood capabilities represents a homogeneous region or pooling-group for regionalization flood frequency analysis (RFFA) [37].

This research adopts the method discussed by [11] to evaluate the effectiveness of regionalization in BORB using the predictive equation of catchment-area ratio obtained for a specific hydrometric region, which relates discharge and area in both gauge and ungauged basins. The equation is expressed by relation 6 [11, 12]:

$$Q_{un} = Q_g \left[\frac{A_{un}}{A_g} \right]^n \quad (6)$$

A further simplification to determine exponent "n" was obtained by taking logarithms of both sides of Eq. (6) to produce Eq. (7):

$$\text{Exponential}(n) = \frac{\log(Q_{un}/Q_g)}{\log(A_{un}/A_g)} \quad (7)$$

where Q_{un} is defined as ungauged site discharge value, Q_g is stream gauging station discharge estimates of interest, A_{un} and A_g are areas of ungauged and gauged site, respectively, in a catchment, while exponent "n" is calculated by analyzing flow characteristics over the basin of concern.

This principle makes the following assumptions:

1. The ungauged catchment basin characteristics (land use, soil, topography, lithology, and geomorphology) are similar to the ones existing at gauged sites in the locality, whether on the same stream or neighboring watershed.

- The model parameters are estimated from a watershed that shares similar hydrology with the ungauged catchment.
- At least A-year (12 months) data exists from temporarily established gauging stations, which can be used to validate simulated data obtained from the NRCS-CN method.
- The ungauged site represents the dependent variable, while the gauge site signifies the independent variable in this method.
- The discharge ratio is assumed equivalent to the ratio of catchment areas of ungauged and gauged raised to a power, "n." The exponent "n" generally varies; however, registered values are between 0.5 and 0.85.
- The exponent relies mostly upon the collective impacts of the decrease in intensity of average rainfall with growing watershed area and the influence of natural storage in the basin.

The areas of both gauge and ungauged sub-basin were delineated using GIS method and substituted into Eq. 7 to obtain exponent "n" for each sub-basin by taking the logarithms of both sides of Eqs. 8, 9, 10 and 11. The drainage areas of gauging sites (A_g) where gauging stations were set up as well as the ungauged areas (A_{un}) of each sub-basin are presented in Table 4 as follows:

$$\text{Okhunwan : } 243,468.5534 = 32,506.65286 \left[\frac{195,750,000}{36,225} \right]^n \quad (8)$$

$$\text{Oyanmi : } 345,343.3802 = 7,824.53 \left[\frac{529,040,000}{51,563} \right]^n \quad (9)$$

$$\text{Owan : } 1,125,421.857 = 39,581.00 \left[\frac{1,216,500,000}{11,186,923} \right]^n \quad (10)$$

$$\text{Osse : } 1,992,682,596 = 191,857.30 \left[\frac{2,228,940,000}{8,200} \right]^n \quad (11)$$

Values of exponent "n" were obtained for each of the 4 sub-basins of Okhunwan, Oyanmi, Owan, and Osse as n_1 ,

n_2 , n_3 , and n_4 , respectively. Mean value ($\bar{n}$) was obtained for the entire basin of Benin-Owena River Basin Development Authority (BORBDA) area by averaging the obtained exponent "n" of the 4 sub-basins utilizing lumped modeling technique, which considers a catchment as a single entity for computations and permit watershed parameters and variables to be averaged over this unit [38, 39]. Therefore, mean $\bar{X}$ value can be obtained from Eq. (12) to standardize ungauged discharge determination at any site within the BORB and enhance practical SHP potential assessment at different locations within the poorly gauged basin:

$$\text{mean } \bar{X} = \frac{n_1 + n_2 + n_3 + n_4}{4} \quad (12)$$

4 Results and discussion

4.1 Catchment characteristics classification

The catchment characteristics needed for the prediction of poorly gauged Okhunwan, Oyanmi, Owan, and Osse sub-catchments were derived through the use of RS and Arc GIS. The characteristics are presented in the form of Tables to show identified parameters, class size, the area covered, percentages of class size, and the implication of the classes in Tables 5, 6, 7, and 8.

Implementation of regionalization was achieved using the catchment-area ratio model, which traditionally transfers discharge-related data from gauged sites to ungauged sites [10–12]. Features considered in the evaluation consist of factors characterizing LULC, topography, hydrology, soil properties, and climatology relating to study area catchments. The introduced technique adequacy is evaluated utilizing Pearson's product-moment correlation coefficient and soil homogeneity test for cross-validation.

4.1.1 Okhunwan sub-basin characteristics

See Table 5

Table 4 Drainage areas of gauged and ungauged sites

S/N	Sub-basin	Sub-basin drainage areas (A_{un}/m^2)	Gauging sites	Gauged site drainage areas (A_g/m^2)
1	Okhunwan sub-basin	195,750,000	Abunwa	36,225
2	Oyanmi sub-basin	529,040,000	Oloma	51,563
3	Owan sub-basin	1,216,500,000	Sabongida	11,186,923
4	Osse sub-basin	2,228,940,000	Isewe	8200

Table 5 Okhunwan catchment characteristic parameters

S/N	Parameters	Class sizes	Area covered (M ²)	Percentage (%)	Result discussion
1	Slope	0–2%	39,695,400	21.56	Flat (21.56%), undulating (51.18%), rolling (23.62%), hilly (3.65%) and mountainous (0%) terrain exists in the sub-basin. 78.44% of the slope can support hydropower development
		2.1–8%	94,242,600	51.18	
		8.1–16%	43,504,200	23.62	
		16.1–30%	6,714,000	3.65	
		> 30.1%	0	0	
2	DEM	25–61.8	18,231,300	9.90	A significant level of elevation exists, which is a function of power potential. This elevation can provide a minimum of 10 m gross hydropower head standard set for this research
		61.81–96.44	38,241,900	20.76	
		96.45–127.46	30,517,200	16.56	
		127.47–158.49	45,435,600	24.66	
		158.5–209	51,801,300	28.12	
3	LULC	Mixed veg	15,291,000	6.90	The sub-basin is heavily vegetated, and this has an impact on CN and runoff values
		Dense veg	162,102,600	73.19	
		Built-up	44,100,000	19.91	
4	CN	26–28	4,776,300	41.98	Only 6.73% of the study region are prone to exceptionally high runoff capability, 9.37% of study zone signifies high runoff capacity with moderate and low runoff capacity classes occupying 22.15% and 61.74% of the investigated sub-basin area, respectively
		29–45	2,248,200	19.76	
		46–48	2,520,000	22.15	
		49–91	1,066,500	9.37	
		92–95	765,900	6.73	
5	Rainfall	25.1–27.1	27,519,685	13.889	Annual rainfall range over the Okhunwan sub-basin is 2214–2452 mm classify on the average as moderately heavy rain
		27.2–28.5	55,363,131	27.941	
		28.6–29.4	61,514,590	31.046	
		29.5–30.7	39,498,842	19.935	
		30.8–33.6	14,245,484	7.190	
6	Identified soil texture	Hydrologic Soil Group			HSG A and B identified which had a good agreement with ground measurement
		A	B	C D	
		Sandy loam	✓		
		Loam	✓		

4.1.2 Oyanmi sub-basin characteristics

See Table 6

4.1.3 Owan sub-basin characteristics

See Table 7

4.1.4 Osse sub-basin characteristics

See Table 8

4.2 Result of rainfall estimation comparability

In this study, PERSIANN $0.25^\circ \times 0.25^\circ$ grid cell satellite-based rainfall data of 2018 were validated by comparing NIMET surface-based precipitation data from synoptic stations of Benin for Okhunwan and Owan sub-basins,

Lokoja for Oyanmi sub-basin, and Akure for Osse sub-basin. The validation was carried out for monthly precipitation, and the analysis was based on a statistical approach using Pearson's product-moment correlation statistics between NIMET and PERSIANN datasets for towns in each sub-basin.

On the average, Okhunwan, Oyanmi, Owan, and Osse sub-basins indicate spatial correlation coefficients of 0.75, 0.65, 0.70, and 0.78, respectively, showing that PERSIANN-CDR is reliable with good dependability status. These outcomes justify the PERSIANN-CDR performance in recent years due to the growing number of training parameters of the artificial neural network by utilization of polar-orbit satellite data in the PERSIANN algorithm, which supports the adoption of PERSIANN-CDR remotely sensed data for this study as against other satellite rainfall estimates such as the Tropical Rain Measurement Mission (TRMM), The Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) datasets to mention a few [40].

Table 6 Oyanmi catchment characteristic parameters

S/N	Parameters	Class sizes	Area covered (M ²)	Percentage (%)	Result discussion	
1	Slope	0–2%	56,391,300	11.33	Flat (11.33%), undulating (45.50%), rolling (21.16%), hilly (13.38%), and mountainous (8.63%) terrain exists in the sub-basin. 88.67% of the slope can support hydropower development	
		2.1–8%	226,404,900	45.50		
		8.1–16%	105,301,800	21.16		
		16.1–30%	66,590,100	13.38		
		> 30.1%	42,936,300	8.63		
2	DEM	194–291.27	107,953,200	21.69	A significant level of elevation exists, which is a function of power potential. This elevation can provide a minimum of 10 m gross hydropower head standard	
		291.28–341.78	178,408,800	35.85		
		341.79–399.76	130,498,200	26.22		
		399.77–478.33	53,685,000	10.79		
		478.34–671	27,079,200	5.44		
3	LULC	Bare/light BU	47,109,600	8.91	The sub-basin is vegetated, and farming activities are high	
		Mixed veg	347,049,900	65.66		
		Dense veg	134,381,700	25.43		
4	CN	13.05–29.81	406,800	27.49	Only 0.49% of the study region is prone to exceptionally high runoff capability, 5.96% of study zone signifies high runoff capacity with moderate and low runoff capacity classes occupying 3.77% and 89.78% of the investigated sub-basin area, respectively	
		29.82–53.76	921,600	62.29		
		53.77–80.71	55,800	3.77		
		80.72–84.00	88,200	5.96		
		84.01–89.39	7200	0.49		
5	Rainfall	17.87–20.74	62,911,680	11.670	Annual rainfall range over the Oyanmi sub-basin is 1401–1590 mm classify on the average as moderate rain and moderately heavy rain	
		20.75–22.92	161,957,248	30.042		
		22.93–24.65	204,866,240	38.001		
		24.66–28.16	109,369,536	20.287		
6	Identified soil texture	Hydrologic Soil Group				HSG A, B and D identified which had a good agreement with ground measurement
		A	B	C	D	
		Sandy loam	✓			
		Loam		✓		
		Clay loam			✓	

4.3 Comparison of observed data with simulated discharge characteristics

Applying the NRCS-CN method to each sub-catchment, Pearson's product-moment showed statistically positive correlations between observed and estimated discharge, mostly within the range of $0.63 < R^2 < 1$ shows a 60% correlation and above for all the sub-basins.

In specifics, an average of 75%, 63%, 68%, and 87% correlation were registered at Okhunwan, Oyanmi, Owan, and Osse sub-basins, which demonstrates that the NRSC-CN model can be utilized to effectively estimate discharges for poorly gauged or ungauged basins and that GIS and RS basin parameters such as LULC determined from satellite images are useful in studying the runoff response of ungauged basins. The research shows that there is an adequate level of complementarity between observed and calculated runoff. The correlation results of estimated discharge across Okhunwan, Oyanmi, Owan, and Osse sub-basins are reasonably acceptable, considering statistical

tests and *p* values as outlined by [41] that *P* values ≥ 0.05 (not significant), < 0.05 (significant), < 0.02 (highly significant). Our analysis showed that the Null hypothesis is correct, i.e., no perceived difference between the observed and calculated parameters. For estimated discharge correlations, each town's entry *p* value alongside the average *p* value of the entire sub-basins are well below 2%, culminating in highly significant statistical results and thus acceptance of the Null hypothesis.

4.4 Spatial patterns of estimated streamflow

The spatial distribution of streamflow obtained using the NRCS-CN model and application of RS and GIS techniques is presented for Okhunwan, Oyanmi, Owan, and Osse sub-basin as spatial discharge map in Figs. 4, 5, 6 and 7 to enable comprehension of the spatial distributions of streamflow [38, 39].

Overall, the discharge characteristics (elevation, slope, LULC, rainfall patterns, etc.) of all the sub-basins plays a

Table 7 Owan catchment characteristic parameters

S/N	Parameters	Class sizes	Area covered (M ²)	Percentage (%)	Result discussion
1	Slope	0–2%	192,918,600	16.86	Flat (16.86%), undulating (53.41%), rolling (22.87%), hilly (6.12%) and mountainous (0.74%) terrain exists in the sub-basin. 83.14% of the slope can support hydropower development
		2.1–8%	611,336,700	53.41	
		8.1–16%	261,778,500	22.87	
		16.1–30%	70,011,000	6.12	
		> 30.1%	8,483,400	0.74	
2	DEM	50–120	258,658,200	22.59953	A high range of elevation which can provide a minimum 10 m gross head needed for hydropower development is available
		130–190	269,534,700	23.54983	
		200–260	217,606,500	19.01275	
		270–330	246,900,600	21.57224	
		340–400	151,829,100	13.26564	
3	LULC	Mixed veg	595,960,041	49.53	The sub-basin is heavily vegetated, and this has an impact on CN and runoff values
		Dense veg	553,206,204	45.98	
		BU/bare earth	53,993,104	4.49	
4	CN	26	559,489,500	45.98	Just 0.01% of the study region is prone to exceptionally high runoff capability, 1.10% of study zone signifies high runoff capacity with moderate and low runoff capacity classes occupying 3.28% and 95.61% of the investigated sub-basin area, respectively
		28	603,845,100	49.63	
		49	39,888,000	3.28	
		89	13,436,100	1.10	
		92	102,600	0.01	
5	Rainfall	14.00–17.00	545,297,400	47.408	Annual rainfall range over the Owan sub-basin is 1630–2133 mm classify on the average as moderate rain and moderately heavy rain
		18.00–19.00	284,127,300	24.702	
		20.00–22.00	263,886,300	22.942	
		23.00–29.00	56,903,400	4.947	
6	Identified soil texture	Hydrologic Soil Group			HSG A & B identified which had a good agreement with ground measurement
		A	B	C D	
		Sandy loam	✓		
		Loam	✓		

substantial role in the characterization of the discharge. Developed zone inside Okhunwan, Oyanmi, Owan, and Osse sub-basins exhibits high curve numbers which expectedly yield high discharge volumes. An outcome that was expected as zones with high curve numbers is portrayed with high volume of discharge. A high curve number represents a high volume of runoff and little infiltration, whereas a small curve number implies little runoff and high-level infiltration [42].

For instance, Adesagbon (CN and average discharge = 94.97, 97,120.493 m³/s), Ogori (CN and average discharge = 82.90, 176,328.120 m³/s), Umokpe (CN and average discharge = 49, 183,273.034 m³/s), and Igbatore (CN = 49, 413,202.486 m³/s) recorded the highest discharges and in contrast towns with the Low CN such as Forest Reserve (CN and average discharge = 27.9451, 3184.501 m³/s), Ojirami (CN = 25.1096, 2250.505 m³/s), Eme (CN = 26, 4879.078 m³/s), Ogbese (CN = 26, 24,264.722 m³/s) within the territories of Okhunwan, Oyanmi, Owan and Osse, respectively. Data on spatial behavior of discharge values are significant in deciding

hydropower potential at various points in this study, particularly as fluctuating sub-basin hydrometric scaling components are relied upon to deliver diverse discharge volumes and qualities. The results of this study are consistent with those of [43], demonstrating good accomplishment in replicating the streamflow indices associated with low and high flows.

4.5 Catchment-area ratio

The results obtained for the four sub-catchments exponent "n" values of Okhunwan, Oyanmi, Owan, and Osse using Eq. 7 and the mean exponent "n" for the entire basin of BORBDA are as presented in Table 9.

Having calculated the discharge at ungauged sites using NRCS-CN model, the only outstanding parameter in the regionalization equation is exponent "n," which was calculated and averaged over the watershed involved showed that the basin has an average value of $n = 0.52$, which falls within the range of values 0.5–0.85 put forward by [44, 45]. This suggests that the developed model can be utilized to

Table 8 Osse catchment characteristic parameters

S/N	Parameters	Class sizes	Area covered (M ²)	Percentage (%)	Result discussion
1	Slope	0–2%	359,957,700	16.99	Flat (16.99%), Undulating (50.43%), Rolling (25.97%), Hilly (5.93%) and Mountainous (0.68%) terrain exists in the sub-basin. 83.01% of the slope can support hydropower development
		2.1–8%	1,068,613,200	50.43	
		8.1–16%	550,264,500	25.97	
		16.1–30%	125,637,300	5.93	
		> 30.1%	14,348,700	0.68	
2	DEM	24–95	706,094,100	33.32485	Acceptable elevation ranges exist, which is a function of power potential. This elevation can provide a minimum of 10 m gross hydropower head standard
		95–66	790,932,600	37.32889	
		166–237	455,316,300	21.48913	
		237–308	164,560,500	7.766606	
		308–379	1,917,900	0.090517	
3	LULC	Bare/BU	286,486,200	12.80611	Most parts of the sub-basin are still under vegetation cover, and only 12.8% built-up activities
		Mixed veg	947,030,400	42.33284	
		Dense veg	1,003,589,100	44.86105	
4	CN	26	1,841,427,900	81.81421	Just 0.66% of the study region is prone to exceptionally high runoff capability, 12.67% of study zone signifies high runoff capacity with moderate and low runoff capacity classes occupying 4.85% and 81.81% of the investigated sub-basin area, respectively
		27–28	109,191,600	4.851357	
		29–44	285,178,500	12.67041	
		45–95	14,945,400	0.664021	
5	Rainfall	7.00–12.00	667,831,680	29.707	Annual rainfall range over the Osse sub-basin is 1577–2204 mm classify on the average as light rain, moderate rain, and moderately heavy rain
		13.00–16.00	905,928,192	40.299	
		17.00–22.00	481,032,384	21.398	
		23.00–30.00	193,251,776	8.596	
6	Identified soil texture	Hydrologic Soil Group			HSG A B and D identified which had a good agreement with ground measurement
		A	B	C D	
		Sandy loam	✓		
		Loam	✓		
		Sandy clay		✓	

compute discharge values for both gauged and ungauged parts of the basin.

Additionally, the exponent " n " permits determination of relationship of ungauged basin characteristics using the flow indicators and watershed characteristics from a catchment with an established relationship [12]. To this end, in order to validate exponent " n " that it can be used in any part of the BORBDA, a soil map of the whole basin is generated in Fig. 8 to identify the soil type present in the entire basin since soil has direct influence on runoff volumes, infiltration, and percolation which are components of this research work and if any of the soil found in BORBDA coverage areas is present in all the four sub-basins of Okhunwan, Oyanmi, Owan and Osse considered in the research. It was confirmed that the HSG A, B, and D found in the four sub-basins are the only HSGs in the entire basin.

5 Conclusion

The paucity of adequate hydrologic data presents serious challenge to proper utilization of water resources in data scarce region of the world, BORBDA and Nigeria inclusive. In such situation, the NRCS-CN method finds useful application. With good degree of agreement between the observed and calculated runoff values, the method and models employed for this study are recommended for field applications in the study basin and other river basins with similar characteristics. This study also facilitates the computation of discharge in ungauged parts of the sub-basins and the entire basin successfully. The obtained exponent " n " values from the catchment-area equations are: $n_1 = 0.23$ (Okhunwan),

Fig. 4 Spatial pattern of discharge in Okhunwan sub-basin

$n_2 = 0.41$ (Oyanmi), $n_3 = 0.71$ (Owan), $n_4 = 0.75$ (Osse) and n -average (BORBDA) = 0.52. This enables the determination of membership of other neighboring sub-basin

around the studied sub-basins, which can be used to determine the hydropower potential of ungauged rivers in the basin. Apart from the fact that the utilization

HSG Maps for the selected watersheds are developed for the study region by interpreting soil maps with the help of Soil Taxonomy which shows HSG A, B and D exists

Fig. 6 Spatial pattern of discharge in Owan sub-basin

in the study area. At the validation phase, the simulated and observed discharge shows a good correlation coefficient of 75%, 63%, 68%, and 87% at Okhunwan, Oyanmi, Owan, and Osse sub-basins, respectively, which

justifies the adequacy of the NRCS-CN model. Based on Pearson's product-moment correlation between NIMET and PERSIANN-CDR datasets, towns in each sub-basin of Okhunwan, Oyanmi, Owan, and Osse signify average

Legend

- Town

NCRS-CN ANNUAL DISCHARGE Qp (m³/s)

- 0 - 1,000
- 2,000 - 5,000
- 6,000 - 30,000
- 40,000 - 50,000
- 60,000 - 85,915

BORBDA basin, there is need to make this research result promptly accessible to committed water resources professionals for use in 11 other river basins in Nigeria and locations around the world with similar challenges of poorly gauged or ungauged basins particularly Africa.

Table 9 Determination of exponent "n" value for BORBDA

S/N	Sub-basin	Exponent "n" value	Mean exponent "n" for entire basin
1	Okhunwan sub-basin	0.23	Mean (n) = $\frac{0.23+0.41+0.71+0.74}{4}$ 0.52
2	Oyanmi sub-basin	0.41	
3	Owan sub-basin	0.71	
4	Osse sub-basin	0.74

Fig. 8 BORBDA soil classification map showing the location of Okhunwan, Oyanmi, Owan, and Osse sub-basins

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights This article does not contain any studies with human or animal subjects performed by any of the authors.

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