

Effect of Hydrologic Soil Groups on Runoff Generation in Reservoir Catchments in Northern Ghana

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ABSTRACT

The study was carried out in northern Ghana to estimate surface runoff in nine (9) reservoir catchments for a period of 20 years (1999–2018) using the United States Department of Agriculture Natural Resource Conservation Service-Curve Number (USDA-NRCS-CN) method. The key input parameters of the method were hydrologic soil group, antecedent moisture condition, rainfall amount, landuse/landcover, weighted curve number and potential maximum soil moisture retention. The annual rainfall within the reservoir catchments was found to vary between 617.2 and 1,382.3 mm. The estimated annual runoff depths ranged from 68.5 ± 7.5 to 98.0 ± 13.3 mm and the percentage annual rainfall converted into runoff varied between 9.8 ± 0.7 and 13.7 ± 0.9 %. Hydrologic soil groups accounted for about 67.2 % and 62.5 % of the variation in runoff depth and percentage runoff respectively, in the reservoir catchments. Catchment size accounted for only 2.7 % and 3.9 % of the variation in runoff depth and the percentage of the amount of rainfall converted into runoff respectively, in the reservoir catchments. Therefore, hydrologic soil groups should be used by reservoir managers as a primary indicator of the potential runoff generation in reservoir catchments.

Keywords: Reservoir catchment, curve number method, northern Ghana, hydrologic soil group, runoff

INTRODUCTION

The primary sources of recharge for surface and groundwater resources are rainfall and runoff (Satheeshkumar *et al.*, 2017). Surface runoff is one of the vital hydrological parameters used in water resources development and maintenance (Bansode and Patil, 2014). Accurate quantification of surface runoff depth and volume generated

from rainfall is a crucial task for proper management of reservoirs constructed for irrigation, as it provides information on water inflow to reservoirs for irrigation scheduling (Amutha and Porchelvan, 2009; Rajbanshi, 2016). The occurrence, quantity and rate of runoff heavily rely on the basic characteristics of a particular rainfall thus the duration, intensity, amount and distribution. Aside the above-mentioned rainfall

parameters, reservoir catchment characteristics such as slope length and steepness, vegetation cover, landuse/landcover types, soil type, shape and size, antecedent moisture condition and infiltration capacity also have a direct impact on the surface runoff generation (Bansode and Patil, 2014; Rajbanshi, 2016). For any given reservoir catchment, runoff volume and peak flow directly depend on the characteristics of the catchment and the infiltration capacity of the catchment and as noted by Patil *et al.* (2008), surface runoff only occurs when the intensity of rainfall is greater than the infiltration rate of the soil.

Various models and methods have been developed and used for the quantification of the volume and depth of surface runoff in ungauged river/stream catchments. Models used for these purposes include; USDA-NRCS Curve Number (USDA-NRCS-CN), Artificial Neural Network (ANN), Geomorphological Instantaneous Unit Hydrograph (GIUH), ARIMA, SWAT, SARIMA, and Fuzzy Models. For long term water inflow estimation, forecasting and modelling, these models are often applied (Rajbanshi, 2016; Pandey and Stuti, 2017).

This study used the USDA-NRCS-CN model. This model is the commonly used model for estimating surface runoff volume and depth from a given rainfall event, because of its low number of input parameters required, simplicity and high accuracy (Bansode and Patil, 2014; Pandey

and Stuti, 2017). Many researchers across the world such as Amutha and Porchelvan (2009), Bansode and Patil (2014), Topno *et al.* (2015), Rajbanshi (2016), Satheeshkumar *et al.* (2017) and Pandey and Stuti (2017) have successfully utilized the USDA-NRCS-CN model to estimate runoff depth and volume in reservoir catchments. Nayak *et al.* (2012) found a high positive correlation between computed inflows using the USDA-NRCS-CN model and observed water inflows in the Uri Watershed (Narmada Basin, India). According to Adongo *et al.* (2016), information on surface runoff in reservoir catchments in northern Ghana are scanty and this has necessitated the current study. This is to provide the requisite information for the management of the studied reservoirs and similar types in similar ecology.

MATERIALS AND METHODS

Study Area

The research was carried out in nine (9) reservoir catchments in three (3) administrative regions of northern Ghana namely; Daffiama, Karni and Sankana reservoir catchments in the Upper West Region; Ve, Tono and Gambibgo reservoir catchments in the Upper East Region and Bontanga, Golinga and Libga dams in the Northern Region of Ghana. The study reservoirs are presented in Figure 1 whilst the detailed description of the reservoirs and their catchments presented in Table 1.

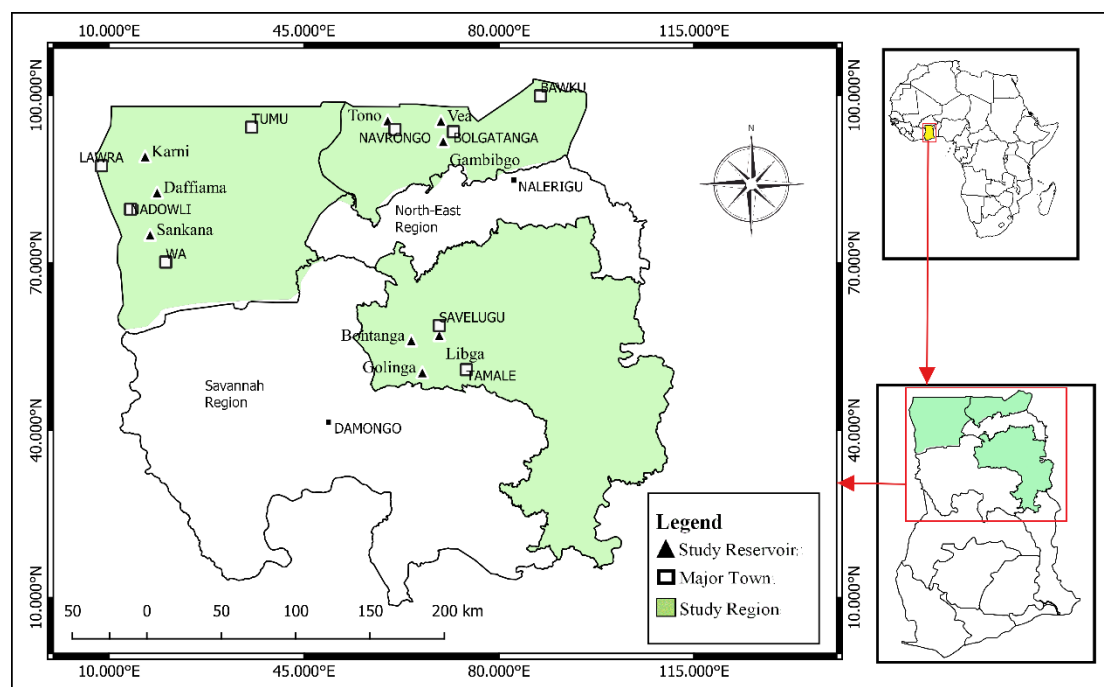


Figure 1: Map of Northern Ghana showing the Location of Study Reservoirs. Adopted and modified from Adongo *et al.* (2019).

Table 1: Description of Study Reservoirs and Catchments

| Regions | | Northern | | | Upper East | | | Upper West | | |
|---|-------------------|--|--------------------|----------------------|--|----------------------|----------------------|---|----------------------|----------------------|
| Reservoirs | | Bontanga | Golinga | Libga | Gambigbo | Tono | Ve | Daffiama | Karni | Sankana |
| Districts | | Kumbungu | Tolon | Savelugu | Bolgatanga | Kassena-Nankana | Bongo | Daffiama-Bussie-Issa | Lambussie-Karni | Nadowli-Kaleo |
| Location Co-ordinates | | N 09°57' W 01°02' | N09°22' W00°57' | N 09°59' W 00°85' | N 10°45' W 00°50' | N 10°52' W 01°08' | N 10°52' W 00°51' | N 10°27' W 02°34' | N 10°40' W 02°38' | N 10°11' W 02°36' |
| Maximum storage capacity of reservoir (10 ⁶ m ³) | | 25 | 1.23 | 0.76 | 0.30 | 93 | 17 | 0.31 | 0.33 | 1.70 |
| Catchment area (km ²) | | 165 | 53 | 31 | 1.70 | 650 | 136 | 21 | 35 | 141 |
| Rainfall Characteristics | Pattern | Unimodal | | | Unimodal | | | Unimodal | | |
| | Annual-Mean (mm) | 1,000 – 1,300 | | | 700 – 1,010 | | | 800 – 1,100 | | |
| | Duration (months) | 5 – 6 | | | 5 – 6 | | | 5 – 6 | | |
| Agro-Ecological Zone (AEZ) | | Guinea-Savanna | | | Guinea/Sudan-Savanna | | | Guinea-Savanna | | |
| Geology of Catchment | | Paleozoic rocks | | | Metamorphic/igneous rocks with sandstone, gneiss, and granodiorite | | | Precambrian, granite and metamorphic rocks | | |
| Soil Classes | | Acrisols, plinthosols, planosols, luvisols, gleysols and fluvisols | | | Plinthosols, luvisols, vertisols, leptosols, lixisols, and fluvisols | | | Lixisols, fluvisols, leptosols, vertisols, acrisols and plinthosols | | |

Adopted and modified from Adongo *et al.* (2019)

The USDA Natural Resource Conservation Service-Curve Number Model

The Natural Resource Conservation Service-Curve Number (NRCS CN) model developed by the United States Department of Agriculture (USDA-NRCS, 1985) was used to estimate water inflows into the study reservoirs. This method was chosen because of its suitability and high accuracy in the estimation and modelling of runoff depth and volume for ungauged river/stream catchments. It calculates direct surface runoff using an empirical formula which requires

daily rainfall amount and a catchment factor as input parameters. The catchment factor is the curve number (CN), which indicates the runoff potential of the landuse/landcover (LULC) of the area. The model uses catchment characteristics such as rainfall, LULC, hydrologic soil group, soil infiltration capability and antecedent-moisture condition of the soil to assign a curve-number (Guptaa and Panigrahya, 2008; Bansode and Patil, 2014). The methodological framework for the estimation of runoff in the study reservoir catchments is illustrated in Figure 2.

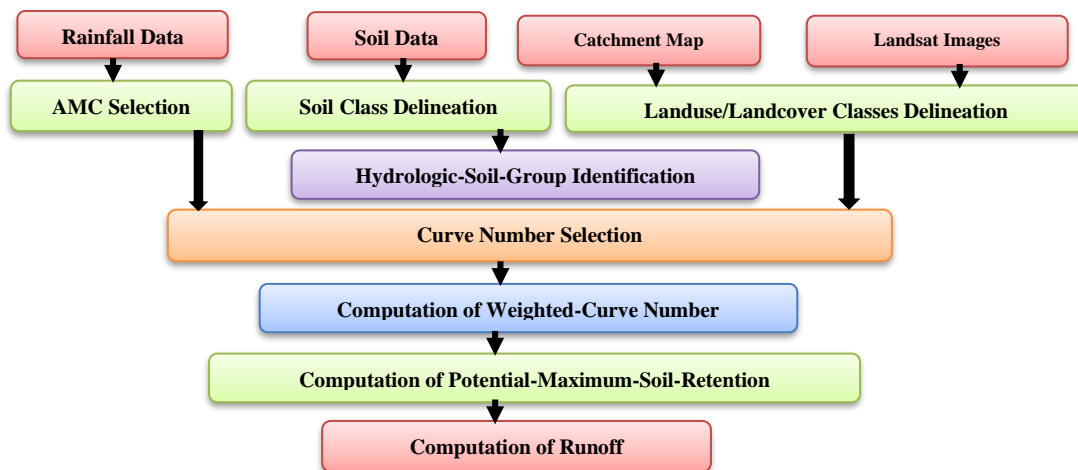


Figure 2: Methodological Framework for Quantification of Surface Runoff in Reservoir Catchment. Adopted and modified from Fan *et al.* (2013)

As a first step, catchment delineation for each reservoir was carried out using the Arc-hydro analyst tool in ArcGIS. The satellite imageries of 2018 (Landsat TM and Landsat 8 OLI) were acquired from the portal of GLOVIS-USGS to prepare the thematic landuse/landcover (LULC) maps of the catchments. A 20-year rainfall data covering 1999–2018 were obtained from the Ghana-Meteorological-Agency (GMA) in Tamale, Bolgatanga and Wa as a primary input for the estimation of water inflow into the study reservoirs. The soil map which indicates the various soil types, classes and hydrologic soil

groups in each reservoir catchment was produced using Ghana soil-shapefile (HWSD, 2017) with the area/region of interest extracted using the area of each reservoir catchment and the soil-data-layer clipped onto the catchment in ArcGIS 10.4 environment.

The Curve Number (CN) which indicates the runoff generation potential of the LULC and the hydrologic soil groups ranges from 0 to 100 and the values were obtained using the method formulated for catchments under various conditions found in the USDA

National Engineering Handbook, Section 4 (USDA-NRCS, 1985). Antecedent-moisture-condition (AMC) values were obtained based on five (5) days of antecedent rainfall before the rainfall event under consideration during a particular dry or growing season (Table 2). Three (3) classes of AMC were identified as

I, II and III corresponding to dry season, moderate season and very wet season. Based on the criteria developed by the USDA-NRCS (1985), each soil class was assigned a hydrologic soil group (HSGs) of 'A', 'B', 'C' or 'D' depending on its texture and infiltration characteristics (Table 3).

Table 1: Antecedent Moisture Conditions (AMC) for different conditions

| AMC Group | Soil Characteristic | Total Rainfall in Previous 5 days (mm) | |
|-----------|---------------------|--|--------------|
| | | Dry Season | Wet Season |
| I | Wet conditions | <13.0 | <36.0 |
| II | Average condition | 13.0 to 28.0 | 36.0 to 53.0 |
| III | Heavy rainfalls | >28.0 | >53.0 |

Adapted from USDA-NRCS (1985)

Table 3: Hydrologic Soil Groups (HSGs)

| HSGs | Soil Texture | Runoff | Rate of Transmission of Water | Terminal Infiltration Rate (mm/h) |
|-----------|--|----------|-------------------------------|-----------------------------------|
| Group 'A' | Well to excessively drained sand or gravel | Low | High | >7.50 |
| Group 'B' | Moderately deep, well-drained with moderate sand or gravel | Moderate | Moderate | 3.80 to 7.50 |
| Group 'C' | Clay loam, shallow-sandy loam, soils with moderate to fine texture | Moderate | Moderate | 1.30 to 3.80 |
| Group 'D' | Heavy clay soils that significantly swell when wet | High | Low | <1.30 |

Adapted from USDA-NRCS (1985)

Computation of Area-Weighted CN and Runoff Depth

The area-weighted CN and runoff depth were computed using Equations 1 and 2 respectively developed by USDA-NRCS (1985):

$$CN_{wt} = \frac{\sum A_i \times CN_i}{\sum A} \quad [1]$$

Where: CN_{wt} – Area weighted curve number; CN_i – Curve number of each LULC class; A_i – Area of each landuse/landcover class (km^2) and A – Area of the catchment (km^2).

$$Q_d = \frac{(P - 0.20S)^2}{P + 0.80S} \quad [2]$$

Where: Q_d – Runoff depth (mm); P – Daily rainfall (mm) and S – Maximum soil

moisture that could be retained after runoff starts (mm).

RESULTS AND DISCUSSION

Input Parameters of the USDA NRCS-CN Model

The USDA-NRCS CN model has its major input parameters as landuse/landcover classes, hydrologic soil groups, antecedent soil moisture conditions, rainfall, maximum potential soil retention, curve number and weighted curve number (USDA-NRCS, 1985). The results of the input parameters are presented in this section.

Landuse and Landcover Classes in the Reservoir Catchments

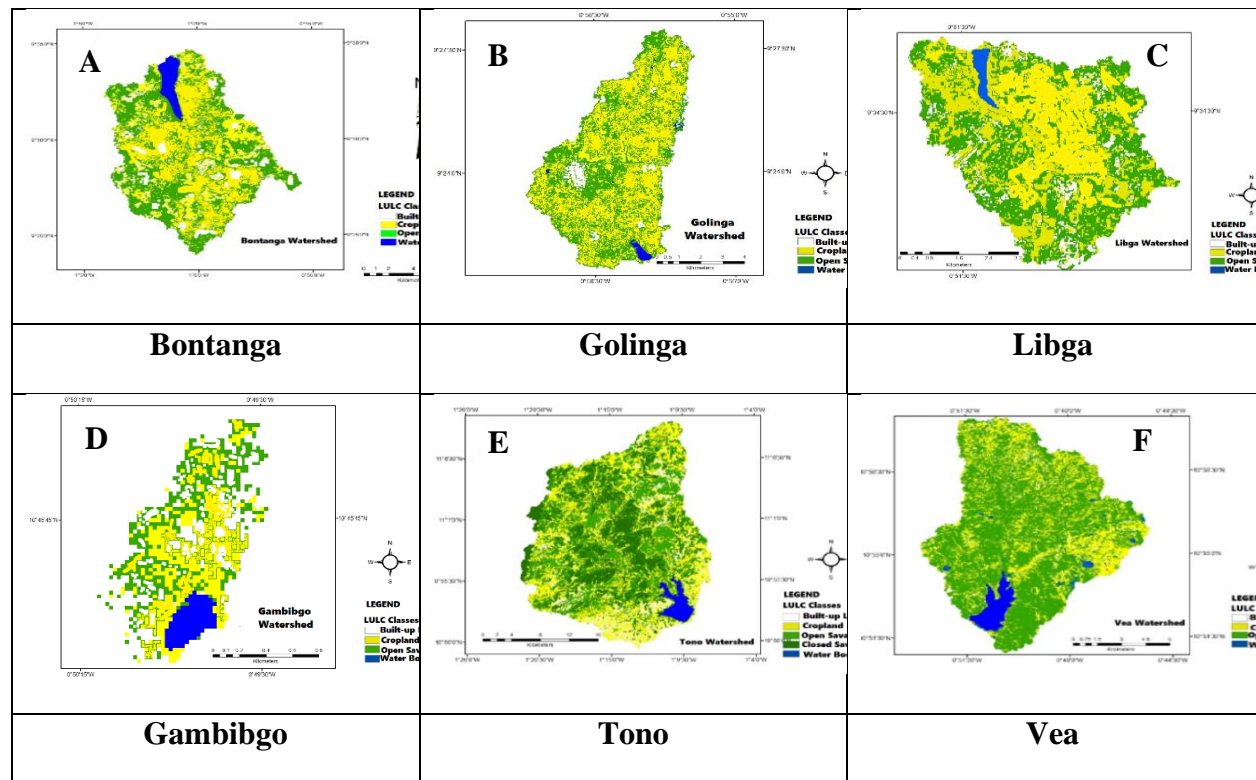
As presented in Table 4 and Figure 3, four major landuse and landcover (LULC) classes namely; built up land, cropland, open savanna woodland and water body were mapped in the catchments of the reservoirs, except Tono catchment where closed savanna woodland was delineated as the 5th major LULC class. In all the reservoir catchments,

cropland occupied the largest area (over 40 %) followed by open savanna woodland except Gambibgo where built-up areas occupied the second largest portion. Rajbanshi (2016) noted that surface runoff is higher on built-up areas, cropland and bareland/rocky lands than on forestlands and woodlands. Closed savanna woodlands with high infiltration potential are only available in the Tono catchment.

Table 4: Landuse/Landcover Classes and their Coverage Area for Year 2016

| LULC | Name of Reservoir Catchment/LULC Areal-Coverage (km ²) for Year 2016 | | | | | | | | | |
|--------------|--|-----------|-----------|------------|------------|------------|-----------|-----------|------------|--|
| | Bontanga | Golinga | Libga | Gambibgo | Tono | Vea | Daffiama | Karni | Sankana | |
| CL | 111.00 | 39.46 | 16.95 | 0.70 | 245.86 | 74.86 | 10.58 | 23.25 | 96.52 | |
| BUL | 8.23 | 3.77 | 7.04 | 0.63 | 79.43 | 10.38 | 3.91 | 3.01 | 8.80 | |
| WB | 7.41 | 0.40 | 0.23 | 0.11 | 16.19 | 5.59 | 0.11 | 0.20 | 0.38 | |
| OSW | 38.36 | 9.37 | 6.78 | 0.26 | 218.60 | 45.17 | 6.40 | 8.54 | 35.30 | |
| CSW | | | | | 89.92 | | | | | |
| | 0.00 | 0.00 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 | 0.00 | |
| Total | 165 | 53 | 31 | 1.7 | 650 | 136 | 21 | 35 | 141 | |

CL – Cropland; LULC – Landuse/landcover; WB – Water bodies; BUL – Built-up land; CSW – Closed-savannah woodland; OSW – Open- savannah woodland



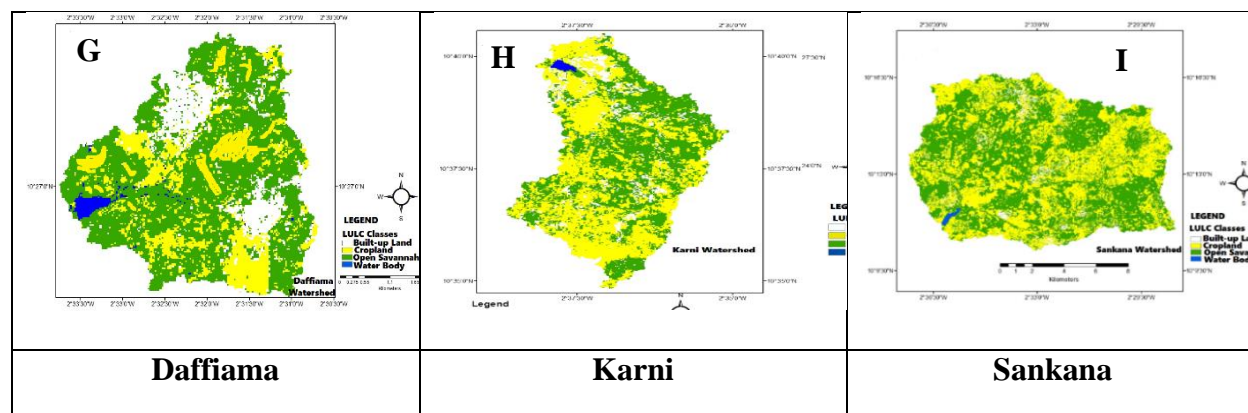


Figure 3: Landuse/Landcover Classes (2016) in Reservoir Catchments (A – I)

Where: White - Built-up areas; Yellow - Cropland; Green - Open savanna woodland; Blue - Water bodies

FAO Soil Classes and Hydrologic Soil Groups (HSGs) in the Reservoir Catchments

The study identified two (2) FAO soil classes in the Daffiama, Gambigbo, Golinga and Libga catchments; three (3) soil classes in the Bontanga, Karni and Sankana catchments; and four (4) soil classes in the Tono and Vea catchments (Table 5 and Figure 4). The FAO soil classes identified in the various catchments included one or more of the following: lixisols, fluvisols, leptosols, vertisols, acrisols, plinthosols and planosols. These soils may belong to one of the hydrologic-soil- group (HSG) 'A', 'B', 'C' or 'D'. According to Amutha and Porchelvan (2009), hydrologic soil groups in a particular

catchment play a very important role in the estimation of runoff depth and volume as they aid in determining the appropriate curve number for each landuse/landcover.

The Bontanga, Golinga and Libga catchments have HSGs 'A' and 'B' whilst the Karni, Daffiama, Sankana, Vea, Tono and Gambigbo catchments have HSGs 'C' and 'D'. As indicated by USDA-NRCS (1985), runoff generation for groups A and B soils are low and high for groups 'C' and 'D' soils. Thus, the influence of the soils in the catchments on runoff generation is low in the Bontanga, Golinga and Libga catchments but high in the other catchments which have their dominant soils being groups 'C' and 'D'.

Table 5: FAO Soil Classes and Their Areal-Coverage in the Study Reservoir Catchments

| FAO Soil Class | HSGs | Name of Catchment/FAO Soil Class Areal-Coverage (km ²) | | | | | | | | |
|----------------|------|--|-------------|-------------|--------------|--------------|-------------|-------------|-------------|--------------|
| | | Bontanga | Golinga | Gambigbo | Tono | Vea | Libga | Daffiama | Karni | Sankana |
| Lixisols | 'D' | - | - | 1.4 | 610.3 | 60.6 | - | - | 0.14 | 47.30 |
| Fluvisol | 'D' | - | - | 0.3 | 23.2 | 13.1 | - | - | - | - |
| Leptosol | 'C' | - | - | - | 16.0 | 53.5 | - | 16.0 | 27.7 | 73.47 |
| Vertisol | 'D' | - | - | - | 0.5 | 8.8 | - | 5.0 | 7.4 | 20.23 |
| Acrisol | 'A' | 68.0 | 40.6 | - | - | - | 25.0 | - | - | - |
| Plinthosol | 'A' | 69.5 | - | - | - | - | - | - | - | - |
| Planosols | 'B' | 27.5 | 12.4 | - | - | - | 6.0 | - | - | - |
| Total | | 165.0 | 53.0 | 1.70 | 650.0 | 136.0 | 31.0 | 21.0 | 35.0 | 141.0 |

FAO – Food and Agriculture Organisation; HSGs – Hydrologic Soil Groups

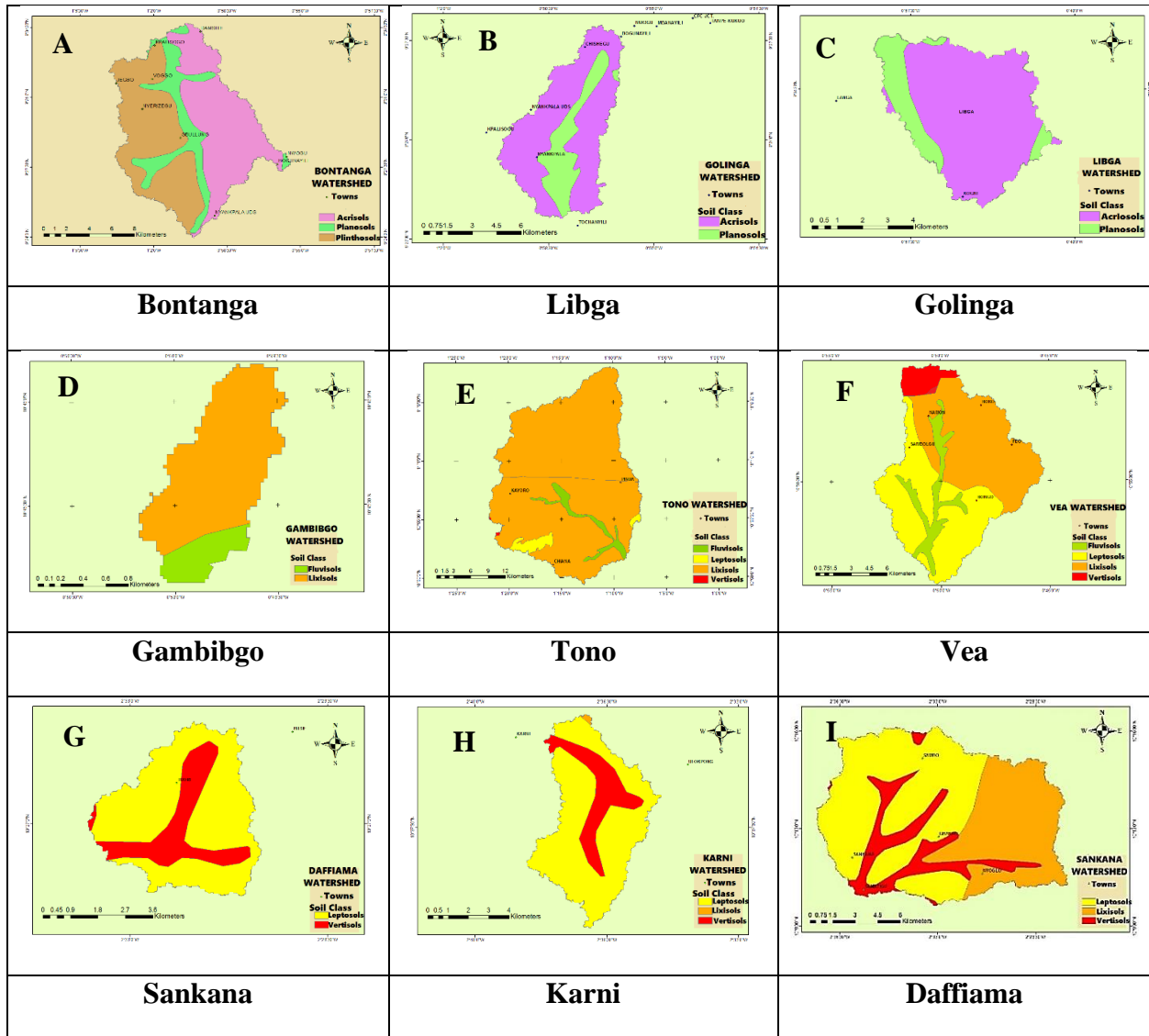


Figure 4: FAO Soil Classes in the Catchments (A – I)

Where: Violet - Acrisols; Light Green - Planosols; Brown - Plinthosols; Deep Green - Fluvisols; Orange - Lixisols; Yellow - Leptosols; Red - Vertisols

Curve Number (CN) and Weighted Curve Number (CNwt)

The highest CN value in the reservoir catchments was 100 for water bodies under any hydrologic soil group and the minimum was 43 for open savannah woodland under hydrologic soil groups ‘A’ and ‘B’ in the Bontanga, Golinga and Libga catchments. For the three (3) levels of antecedent moisture conditions (AMC I–III), the

computed weighted CN revealed that reservoir catchments with HSGs ‘C’ and ‘D’ recorded high values of 62–94 while reservoir catchments with HSGs ‘A’ and ‘B’ recorded low values of 38–79 (Table 6). According to USDA-NRCS (1985), lower CN and CNwt values indicate the low potential of runoff generation while higher CN and CNwt values indicate high runoff potential. This suggests that Sankana, Karni,

Daffiama, Tono, Gambibgo and Vea catchments could generate runoff higher than

that of Bontanga, Golinga and Libga catchments.

Table 6: CN and CNwt Values for Different LULC Classes and HSGs in the Catchments

| Catchment | LULC | HSG(s) | Area (km ²) | CN | CNwt |
|-----------|------|-----------|-------------------------|-----|------------|
| Bontanga | CL | 'A' & 'B' | 111.00 | 64 | AMC-1 = 40 |
| | BUL | 'A' | 8.23 | 72 | AMC-2 = 60 |
| | WB | 'A' & 'B' | 7.41 | 100 | AMC-3 = 78 |
| | OSW | 'A' & 'B' | 38.36 | 43 | |
| Golinga | CL | 'A' & 'B' | 39.46 | 65 | AMC-1 = 42 |
| | BUL | 'A' & 'B' | 3.77 | 74 | AMC-2 = 62 |
| | WB | 'A' & 'B' | 0.40 | 100 | AMC-3 = 79 |
| | OSW | 'A' & 'B' | 9.37 | 43 | |
| Libga | CL | 'A' & 'B' | 17.95 | 64 | AMC-1 = 38 |
| | BUL | 'A' & 'B' | 4.04 | 74 | AMC-2 = 58 |
| | WB | 'A' & 'B' | 0.23 | 100 | AMC-3 = 76 |
| | OSW | 'A' & 'B' | 8.78 | 43 | |
| Gambibgo | CL | 'D' | 0.70 | 85 | AMC-1 = 73 |
| | BUL | 'D' | 0.63 | 89 | AMC-2 = 87 |
| | WB | 'D' | 0.11 | 100 | AMC-3 = 94 |
| | OSW | 'D' | 0.26 | 80 | |
| Tono | CL | 'C' & 'D' | 245.86 | 85 | AMC-1 = 67 |
| | BUL | 'C' & 'D' | 79.43 | 89 | AMC-2 = 83 |
| | WB | 'D' | 16.19 | 100 | AMC-3 = 93 |
| | OSW | 'C' & 'D' | 198.60 | 80 | |
| | CSW | 'C' & 'D' | 109.92 | 77 | |
| Vea | CL | 'C' & 'D' | 74.86 | 83 | AMC-1 = 66 |
| | BUL | 'C' & 'D' | 10.38 | 88 | AMC-2 = 82 |
| | WB | 'C' & 'D' | 5.59 | 100 | AMC-3 = 92 |
| | OSW | 'C' & 'D' | 45.17 | 78 | |
| Daffiama | CL | 'C' & 'D' | 10.58 | 83 | AMC-1 = 64 |
| | BUL | 'C' | 3.23 | 87 | AMC-2 = 81 |
| | WB | 'C' & 'D' | 0.11 | 100 | AMC-3 = 92 |
| | OSW | 'C' & 'D' | 7.08 | 75 | |
| Karni | CL | 'C' & 'D' | 22.25 | 82 | AMC-1 = 63 |
| | BUL | 'C' | 3.01 | 87 | AMC-2 = 80 |
| | WB | 'D' | 0.20 | 100 | AMC-3 = 91 |
| | OSW | 'C' & 'D' | 9.54 | 75 | |
| Sankana | CL | 'C' & 'D' | 91.26 | 83 | AMC-1 = 62 |
| | BUL | 'C' & 'D' | 4.40 | 88 | AMC-2 = 79 |
| | WB | 'C' & 'D' | 0.38 | 100 | AMC-3 = 91 |
| | OSW | 'C' & 'D' | 44.20 | 77 | |

CL – Cropland; LULC – Landuse/landcover; WB – Water bodies; BUL – Built-up land; CSW – Closed-savannah woodland; OSW – Open- savannah woodland; HSGs – Hydrologic soil groups; CN – Curve number; CNwt – Weighted curve number; AMC – Antecedent moisture condition

Annual Rainfall in the Study Reservoir Catchments

The annual rainfall within the study reservoir catchments for the period of 1999–2018 is presented in Table 7 and Figure 5.

Table 7: Annual rainfall of the study reservoir Catchments from 1999–2018

| Reservoir | Region | Average | |
|-----------|------------|----------------------|----------------------|
| | | Annual Rainfall (mm) | Annual Rainfall (mm) |
| Bontanga | Northern | 791.3–1,382.3 | 1,063.3 |
| Golinga | Northern | 817.7–1,357.6 | 1,049.2 |
| Libga | Northern | 792.3–1,381.3 | 1,067.7 |
| Gambibgo | Upper East | 732.9–1,268.9 | 962.7 |
| Tono | Upper East | 617.2–1,365.0 | 995.9 |
| Vea | Upper East | 732.9–1,265.9 | 944.4 |
| Daffiama | Upper West | 812.2–1,291.1 | 1,057.6 |
| Karni | Upper West | 814.4–1,291.2 | 1,065.8 |
| Sankana | Upper West | 811.6–1,292.3 | 1,049.5 |

The annual rainfall within the reservoir catchments for the 20 years (1999–2018) ranged from 617.2 to 1,382.3 mm, with average annual rainfall for those in the Northern, Upper East and Upper West Regions varying between 1,049.2 and 1,067.7 mm, 944.4 and 995.9 mm and 1,049.5 and 1,065.8 mm respectively, as in Table 7. Rajbanshi (2016) observed a strong

positive correlation between annual rainfall and an annual volume of water inflow into the Konar reservoir in India and further stated that the reservoir received low water inflows in years with annual rainfalls less than 960.1 mm. The lowest and highest annual rainfalls were recorded in the Tono catchment in 2014 and Libga catchment in 1999, respectively, as observed in Figure 5.

At the Bontanga and Libga catchments, annual rainfall less than the average rainfall was recorded in 2000–2002, 2006, 2013–2017, whilst the rest of the years had annual rainfall over the average. At the Golinga catchment, annual rainfall less than the average rainfall was recorded in 2001, 2002, 2005–2007, 2014, 2015 and 2017, whilst the rest of the years had annual rainfall above the average (Table 7 and Figure 5).

At Gambibgo and Vea catchments, annual rainfall less than the average rainfall was recorded in 2000, 2002, 2004–2006, 2008, 2011, 2013–2015, whilst the rest of the years had annual rainfall over the average. At Tono catchment, annual rainfall less than the average rainfall was recorded in 2001, 2002, 2005, 2006, 2009, 2013–2015, whilst the rest of the years had annual rainfall above the average. At Daffiama, Karni and Sankana catchments, annual rainfall less than the average rainfall was recorded in 2001, 2002, 2006, 2007, 2011, 2014–2017, whilst the rest of the years had annual rainfall above the average (Table 7 and Figure 5).

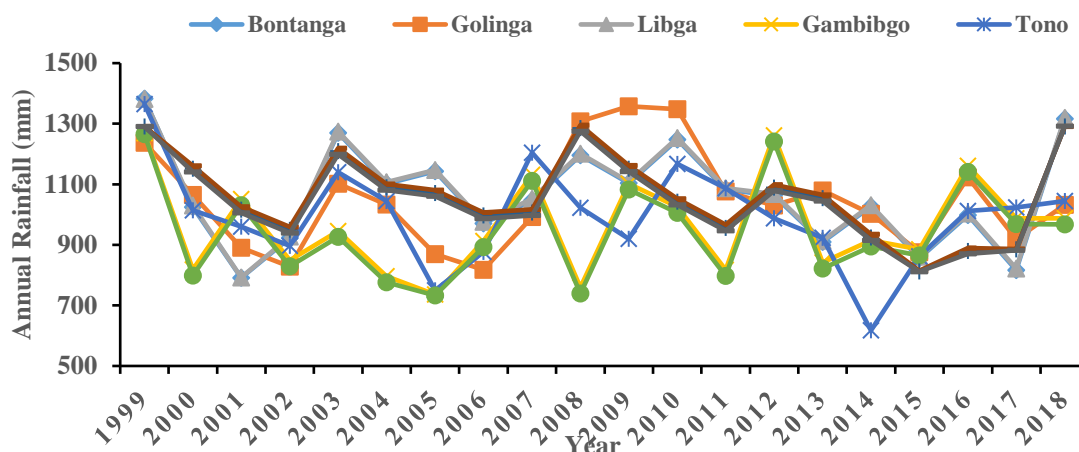


Figure 5: Annual Rainfall in the Study Reservoir Catchments for the Period of 1999-2018

Estimated Annual Runoff Depths and Percentage Annual Runoff in Study Reservoir Catchments

Estimated Annual Runoff Depths and Percentage

The estimated annual runoff depths and percentage annual runoff for each of the study reservoir catchments for the period of 1999-2018 are presented in Table 8.

Table 8: Estimated Runoff Depths and Percentage Annual Runoff in Study Reservoir Catchments

| Period | 1999-2018 | |
|-----------|-------------------------------|----------------------|
| Reservoir | Mean Annual Runoff Depth (mm) | Mean % Annual Runoff |
| Bontanga | 68.55 ± 7.51 | 9.77 ± 0.66 |
| Golinga | 73.78 ± 7.85 | 10.86 ± 1.07 |
| Libga | 70.39 ± 8.30 | 9.95 ± 0.66 |
| Gambibgo | 98.01 ± 13.25 | 13.67 ± 0.93 |
| Tono | 87.07 ± 6.76 | 13.23 ± 1.17 |
| Vea | 86.84 ± 10.67 | 13.09 ± 1.78 |
| Daffiama | 86.94 ± 4.75 | 12.52 ± 1.15 |
| Karni | 84.34 ± 6.29 | 12.13 ± 2.13 |
| Sankana | 91.71 ± 10.24 | 13.21 ± 0.69 |

Values are means ± standard deviation

The estimated annual runoff depths generated from the rainfall over the 20 years ranged from 54.10 to 125.55 mm, with the average runoff depths varying between 68.55 ± 7.51

mm at Bontanga and 98.01 ± 13.25 mm at Gambibgo (Table 8). The values are lower than the estimated average annual runoff depths of 159.05 mm and 576.14 mm, respectively, recorded at the Malattar catchment in India (Amutha and Porchelvan, 2009) and the Upper South Koel catchment in Jharkhand, India (Pandey and Stuti, 2017). The Malattar and Upper Koel catchments with similar climatic, soil and LULC characteristics as that of the study reservoir catchments under discussion.

As presented in Table 8, lower runoff depths were recorded at the Bontanga, Golinga and Libga and this could be attributed to the predominance of group A and B soils in their catchments. These soils have high infiltration rates and low runoff potentials as indicated by USDA-NRCS (1985). On the other hand, higher runoff depths were recorded in the Vea, Gambibgo, Tono, Sankana, Daffiama and Karni and this could also be due to the dominance of groups C and D soils in their catchments.

The study found the percentage proportion of annual rainfall in the catchments converted into the runoff for their corresponding reservoirs range from 9.77 ± 0.66 to 13.67 ± 0.93 %, as presented in Table 8. The results

show that the catchments have low runoff characteristics. Rajbanshi (2016) recorded an annual runoff coefficient of 6.31 % in the Konar catchment located in India and described it as a catchment with low runoff potentials. Whiles, Amutha and Porchelvan (2009) recorded a high annual runoff coefficient of 32.02 % at the Malattar Sub-catchment in India. Also, Pandey and Stuti (2017) described the Upper South Koel catchment in Jharkhand as characterized by high runoff discharge with about 59.32 % of the annual rainfall converted into a surface runoff in five (5) monsoon seasons.

Effect of Soil Classes on Annual Runoff Depths and Percentage Annual Runoff

The dominant soil classes in the Bontanga, Golinga and Libga catchments are classified under HSGs 'A' and 'B' soils whilst the Vea, Gambibgo, Tono, Sankana, Karni and Daffiama catchments have their dominant soils classified under HSGs 'C' and 'D'. The estimated annual runoff depths for reservoir catchments with groups 'A' and 'B' soils were found to range from 68.55 to 73.78 mm

with an average of 70.91 ± 7.89 mm, whilst the annual runoff depths for reservoir catchments with groups 'C' and 'D' soils were found to range from 84.34 to 98.01 mm with an average of 89.15 ± 8.66 mm.

An independent-sample *t*-test comparing the annual runoff depths based on groups 'A' and 'B', and 'C' and 'D' soils are presented in Tables 9a and 9b. The results indicated that there was a significant difference in annual runoff depths for groups 'A' and 'B' soils compared to groups 'C' and 'D' soils. The extent of the mean difference was very large ($\eta^2 = 0.672$). Hence, the effect of hydrologic soil groups on annual runoff depth measured by the η^2 is 67.2 %. This implies that hydrologic soil groups account for about 67.2 % of the variance in annual runoff depths in the catchments. This is very large according to the guidelines given by Cohen (2013). It was, therefore, noted that soil types/classes with their direct effect on hydrologic soil groups have a very significant influence on the generation of runoff in catchments.

Table 9a: Independent Samples Test of Annual Runoff Depths Across Hydrologic Soil Groups

| Variable | HSGs | N | M | Std. Deviation | Std. Error Mean |
|-------------------|-----------|---|-------|----------------|-----------------|
| Runoff Depth (mm) | 'A' & 'B' | 3 | 70.91 | 7.89 | 4.56 |
| | 'C' & 'D' | 6 | 89.15 | 8.66 | 3.54 |

N – Number of samples; *Std.* – Standard; *HSGs* – Hydrologic soil groups; *M* – Mean; 'A' – Acrisols; 'B' – Planosols; 'C' – Leptosols; 'D' – Lixisols/Fluvisols/Verstisols

Table 9b: Independent Samples Test of Annual Runoff Depths Across Hydrologic Soil Groups

| Variable | Assumptions | LTVE | | t-test for Means Equality | | | | | | | | |
|--------------|-------------|------|------|---------------------------|------|------------------|-------|------|----------|------|--|--|
| | | F | Sig. | t | df | Sign. (2-tailed) | MD | SED | 95 % CID | | | |
| | | | | | | Lower | Upper | | | | | |
| Runoff Depth | EVA | 2.45 | 0.01 | -3.85 | 7.00 | 0.012 | 18.24 | 5.34 | -34.36 | 6.86 | | |
| | EVNA | | | -3.52 | 6.31 | 0.005 | 18.24 | 7.62 | -35.12 | 6.77 | | |

LTVEV- Levene's Test for Variances Equality; *EVNA*-Equal variances not assumed; *EVA*-Equal variances assumed; *CID*-Confidence Interval Difference; *SED*-Std. Error Difference; *MD*-Mean Difference

Furthermore, the study found that the percentage annual runoff for catchments with

HSGs 'A' and 'B' soils ranged from 7.96 to 12.38 % with an average of 9.89 ± 0.80 %,

whilst the catchments with HSGs ‘C and ‘D’ recorded 9.98–16.34 % with an average of 12.98 ± 1.14 %. It was observed that a lower percentage annual runoff was recorded under HSGs ‘A’ and ‘B’, whilst higher values were recorded under the ‘C and ‘D’ HSGs. This could be attributed to the high infiltration rates and low runoff potentials of HSGs ‘A’ and ‘B’, whereas the ‘C and ‘D’ HSGs are reported to have low infiltration rates and high runoff potentials (USDA-NRCS, 1985). An independent-sample *t*-test was performed to statistically determine whether there was a significant difference between the percentage annual runoff for groups ‘A’ and ‘B’ and ‘C’

and ‘D’ soils. The results are presented in Tables 10a and 10b.

The results indicated that there was a significant difference in percentage annual runoff for HSGs ‘A’ and ‘B’ ($M = 9.89$, $SD = 0.80$) and ‘C’ and ‘D’. The extent of the mean difference was very large ($\eta^2 = 0.625$). Hence, the effect of soil classes and hydrologic soil groups on the percentage annual runoff estimated by the η^2 is 62.5 %. This implies that soil classes and hydrologic soil groups accounted significantly for about 62.5 % of the variation in the percentage annual runoff in the catchments.

Table 10a: Group Statistics of Independent Samples Test of Percentage Annual Runoff Across Hydrologic Soil Groups

| Variable | HSGs | N | M | Std. Deviation | Std. Error Mean |
|-----------------|-----------|---|-------|----------------|-----------------|
| % Annual Runoff | ‘A’ & ‘B’ | 3 | 9.89 | 0.80 | 0.46 |
| | ‘C’ & ‘D’ | 6 | 12.98 | 1.14 | 1.07 |

N – Number of samples; *Std.* – Standard; *HSGs* – Hydrologic soil groups; *M* – Mean; ‘A’- Acrisols; ‘B’ – Planosols; ‘C’ – Leptosols; ‘D’ – Lixisols/Fluvisols/Verstisols

Table 10b: Independent Samples Test of Percentage Annual Runoff across Hydrologic Soil Groups

| Variable | Assumptions | LTVE | | t-test for Means Equality | | | | | | |
|-----------------|-------------|------|------|---------------------------|------|------------------|------|-------|----------|-------|
| | | F | Sig. | t | df | Sign. (2-tailed) | MD | SED | 95 % CID | |
| | | | | | | | | Lower | Upper | |
| % Annual Runoff | EVA | 1.05 | 0.02 | -5.35 | 7.00 | 0.003 | 3.08 | 0.79 | -4.75 | -1.67 |
| | EVNA | | | -4.11 | 6.17 | 0.025 | 3.08 | 1.42 | -3.69 | -0.88 |

LTVE- Levene's Test for Variances Equality; *EVNA*-Equal variances not assumed; *EVA*-Equal variances assumed; *CID*-Confidence Interval of the Difference; *SED*-Std. Error Difference; *MD*-Mean Difference

Effect of Catchment Size on Annual Runoff Depths and Percentage Annual Runoff

According to Singh (1994), reservoir catchments of area $< 250 \text{ km}^2$, $250 - 2,500 \text{ km}^2$ and $> 2,500 \text{ km}^2$ are classified as small, medium and large-sized catchments respectively. Based on this classification, all the study reservoir catchments are small except the Tono catchment which is a

medium-sized catchment. However, for this study, the reservoir catchments were classified into two (2) namely; reservoir catchments $\leq 100 \text{ km}^2$ which are Gambibgo, Daffiama, Libga, Karni and Golinga and catchments $> 100 \text{ km}^2$ which are Ve, Sankana, Bontanga and Tono. The study found that annual runoff depths in the reservoir catchments $\leq 100 \text{ km}^2$ ranged from 54.1 to 125.6 mm with a mean of 82.7 ± 12.9

mm, whilst annual runoff depths in catchments $> 100 \text{ km}^2$ ranged from 56.7 to 111.1 mm with a mean of 83.5 ± 12.5 mm.

An independent sample t-test was conducted to compare annual runoff depths based on catchments $\leq 100 \text{ km}^2$ and $> 100 \text{ km}^2$ with the results presented in Tables 11a and 11b. The results revealed that there was no significant difference between annual runoff depths in

catchments $\leq 100 \text{ km}^2$ and $> 100 \text{ km}^2$. The magnitude of the difference in the means was very small ($\eta^2 = 0.027$). Hence, the effect of catchment size on the annual runoff depth estimated by the η^2 is 2.7 %. This implies that catchment size accounts for only about 2.7 % of the variation in annual runoff depths in reservoir catchments. Thus, catchment size has an insignificant influence on runoff generation in reservoir catchments.

Table 11a: Group Statistics of Independent Samples Test of Annual Runoff Depth Across Catchment Sizes

| Variable | HSGs | N | M | Std. Deviation | Std. Error Mean |
|-------------------|-------------------------|---|-------|----------------|-----------------|
| Runoff Depth (mm) | $\leq 100 \text{ km}^2$ | 5 | 82.69 | 12.99 | 5.81 |
| | $> 100 \text{ km}^2$ | 4 | 83.54 | 12.52 | 6.26 |

N – Number of samples; *Std.* – Standard; *HSGs* – Hydrologic soil groups; *M* – Mean

Table 11b: Independent Samples Test of Annual Runoff Depth Across Catchment Sizes

| Variable | Assumptions | LTVE | | t-test for Means Equality | | | | MD | SED | 95 % CID | |
|--------------|-------------|------|------|---------------------------|------|------------------|-------|------|--------|----------|--|
| | | F | Sig. | t | df | Sign. (2-tailed) | Lower | | | Upper | |
| Runoff Depth | EVA | 0.04 | 0.85 | 0.22 | 7.00 | 0.84 | 0.85 | 0.79 | -19.85 | 23.55 | |
| | EVNA | | | 0.21 | 4.01 | 0.82 | 0.85 | 1.42 | -22.39 | 26.06 | |

LTVE- Levene's Test for Variances Equality; *EVNA*-Equal variances not assumed; *EVA*-Equal variances assumed; *CID*-Confidence Interval Difference; *SED*-Std. Error Difference; *MD*-Mean Difference

The percentage annual runoff in the reservoir catchments $\leq 100 \text{ km}^2$ was found to range from 7.9 to 14.8 %, with a mean of 11.8 ± 1.6 % whilst percentage annual runoff in catchments $> 100 \text{ km}^2$ ranged from 8.8 to 16.3 % with a mean of 12.3 ± 1.9 %. An independent-sample *t-test* was conducted to compare the percentage annual runoff in catchments $\leq 100 \text{ km}^2$ and $> 100 \text{ km}^2$ with the results presented in Tables 12a and 12b. The

results indicated that there was no significant difference in percentage annual runoff in catchments $\leq 100 \text{ km}^2$ and $> 100 \text{ km}^2$. The extent of the mean difference was very small ($\eta^2 = 0.039$). Thus, the catchment size accounts for only about 3.9 % of the variation in the percentage of the amount of rainfall converted into runoff in the reservoir catchments and therefore does not influence significantly runoff generation.

Table 12a: Group Statistics of Independent Samples Test of Percentage Annual Runoff Across Catchment Sizes

| Variable | HSGs | N | M | Std. Deviation | Std. Error Mean |
|-----------------|-----------------------|---|-------|----------------|-----------------|
| % Annual Runoff | $< 100 \text{ km}^2$ | 5 | 11.81 | 1.61 | 0.72 |
| | 100-650 km^2 | 4 | 12.33 | 1.87 | 0.94 |

N – Number of samples; *Std.* – Standard; *HSGs* – Hydrologic soil groups; *M* – Mean

Table 12b: Independent Samples Test of Percentage Annual Runoff Across Catchment Sizes

| Variable | Assumptions | LTVE | | t-test for Means Equality | | | | MD | SED | 95 % CID | |
|-----------------|-------------|------|------|---------------------------|------|---------------------|-------|------|-------|----------|--|
| | | F | Sig. | t | df | Sign. (2-tailed) | Lower | | | Upper | |
| % Annual Runoff | EVA | 0.20 | 0.67 | -0.11 | 7.00 | 0.92 | -0.52 | 1.23 | -3.29 | 3.02 | |
| | EVNA | | | -0.12 | 5.83 | 0.91 | -0.52 | 1.19 | -3.24 | 2.97 | |

LTVE- Levene's Test for Variances Equality; EVNA-Equal variances not assumed; EVA-Equal variances assumed; CID-Confidence Interval Difference; SED-Std. Error Difference; MD-Mean Difference

CONCLUSIONS

The USDA-NRCS-CN method successfully estimated runoff depths in the study reservoir catchments for a period of 20 years (1999–2018). The annual rainfall within the reservoir catchments fluctuated during the past 20 years and it varied between 617.2 and 1,382.3 mm. The study found that catchments of reservoirs in northern Ghana have low runoff characteristics with annual runoff depths ranging from 68.5 ± 7.5 to 98.0 ± 13.3 mm and the percentage annual rainfall converted into runoff varying between 9.8 ± 0.7 and 13.7 ± 0.9 %.

The study found that hydrological soil groups determine by soil type and class have a significant influence on runoff depths and percentage annual runoff in the reservoir catchments. Reservoir catchments dominated with HSGs 'A' and 'B' gave lower runoff depths compared to 'C' and 'D' HSGs. Hydrologic soil groups accounted for about 67.2 % and 62.5 % of the variation in annual runoff depth generated and percentage annual runoff respectively. The study also found that the size of a reservoir catchment has no significant influence on runoff depth and percentage annual runoff. Catchment size accounted for only about 2.7 % and 3.9 % of the variation in annual runoff depth and percentage rainfall converted into runoff respectively. Thus, soil type and class should be used as a primary indicator of the potential runoff generation in reservoir catchments by managers of such reservoirs.

Conflict of Interest

The author declared that there has not been any conflict of interest regarding the publication of this article.

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