Determination of Physiographic Characteristics of an Ungauged Watershed in North Central Nigeria

O O Olla1, K A Adeniran2, M Y Kasali1 and D James1

1Land and Water Management Engineering Department, National Centre for Agricultural Mechanization (NCAM), Ilorin, Nigeria.
2Agricultural and Biosystems Engineering Department, University of Ilorin, Ilorin, Nigeria.

Email: femiolla2014@gmail.com

Abstract. Watershed characteristics such as basin length, shape, area, stream order, drainage density and stream density are some of the factors affecting various aspects of runoff. This research work presents the determination of some physiographic and geological factors of a small catchment in North Central Nigeria. The perimeter of the catchment was delineated with the aid of a Global Positioning System (GPS) using the co-ordinate of the concrete dam located at Elerinjare community and software such as Google Earth and ArcGIS were also utilized. The catchment was found to include some local communities among which are Okanle, Fajeromi, Amodu-Asungholu, Igberi, Arugbo, Irapa and Basanyin. The total Basin Area for the catchment determined using ArcGIS, was found to be 61.115 km², with the total length of the catchment as 13.598 km. Other catchment characteristics determined include the catchment drainage density, found to be 0.656; this is an indication of the drainage condition within the catchment; higher drainage densities are expected where the soils are easily eroded, or relatively impermeable, with steep slopes and scanty vegetation. The average length of overland flow within the basin is indirectly proportional to the drainage density within the watershed, it was determined to be 0.62/km for this catchment. The stream density/stream frequency was found to be 0.245/km². Some of the factors determining the shape of the basin were also determined; these include the circulatory ratio, elongation ratio and compactness coefficient, found to be 0.327, 0.649 and 1.749/km, respectively. This study reveals the physical/hydrological characteristics of this watershed that will lead to hydrological modeling of the watershed for water resource utilization for the communities located within the watershed.

1. Introduction

A catchment can be defined by highpoints and ridgelines that descend into lower elevations and stream valleys. In other words, a watershed describes an area of land that contains a common set of streams and rivers that all drain into a single larger body of water, such as a larger river, a lake or an ocean. The whole area of a river basin from where all surface runoff (due to a storm) drains into the river in the basin is considered as a hydrologic unit. Hydrological studies of a catchment are very important as a result of its key role in the conception and design of storage reservoir schemes. The studies relate to the total quantity of water available at a particular reservoir site and the best method of regulating, controlling and using the resources.

Catchment water balance assessment is an important factor in pre-requisite to understanding the key processes of the hydrologic cycle. However, the challenge is pronounced in developing countries due to scarcity of data on climate and runoff; this is true for many river basins in Nigeria. Though processes such as precipitation, evaporation and infiltration take place everywhere on the land surface, the resulting
runoff passes through but one point in the stream. Insufficient runoff data is one of the major problems of watershed management in Nigeria [1]: Some of the reasons for the aforementioned problem includes inadequate funding, lack of adequate manpower, lack of necessary equipment, inaccessibility of some of the gauge stations, lack of political will, among others.

A catchment is ungauged or poorly gauged in relation to a variable of interest. In addition, according to Sivapalan et. al. [2], an ungauged catchment is in respect of a variable of interest. He further corroborated the fact with the prediction of ungauged basins (PUB) made by the International Association of Hydrologic Sciences (IAHS) by predicting hydrological responses for ungauged basins and its associated uncertainty for the year 2003-2012. Estimation of continuous streamflow is an important issue in surface hydrology, especially in ungauged watersheds. Sivapalan et al. [2] described ungauged watersheds as one with inadequate records (both in data quantity and quality) of hydrological observations. Watershed characteristics are of different types and they are used to measure different hydrological attributes; important among these characteristics is the drainage density; which was described by Rodriguez-Iturbe and Escobar [3] as a variable representing the interaction between climate and geomorphology; [4]. Sreenivasulu and Bhaskar [5] also described it as a measure of climate, vegetation and topography.

The ability of the basin to discharge its water is largely determined by its drainage density, the implication of which can be seen in flood management while texture topography is the level of topography dissection and Relief gradient is indicative of the differences in elevation. Bifurcation ratio can be defined as a measure of how one basin order discharges water into another; this is also relevant in hydrograph time relation [1]; as bifurcation ratio reduces, with an increase in flood incidence. The shape of a basin affects the time of peak, time of concentration and peak drainage.

It could be deduced from the preliminary investigation carried out by Sule et al., [6] that the concrete dam built across the Odomu River, a tributary of Oyun River by the Kwara State Government and the authority of the National Centre for Agricultural Mechanization (NCAM) is presently being under-utilized. The dam is an ungauged dam with a design capacity of 50 million m³ but only supplies potable water to the dwellers of Idofian and Elerinjare communities, only with a treatment plant of less than 10 m³; the water distribution design carried out by Olla [7] revealed an additional total capacity of less than 4 m³; all these still reveal under-utilization of the resources. Majority of the communities within this catchment are without potable water probably due to lack of information on the potential of the available discharge within the catchment to supply the needed discharge and to extend potable water to lacking communities, e.g. communities such as Arugbo, Amodu, Basanyin, Irapa, etc. are without potable water; most of the inhabitants depend on shallow wells for their drinking water use. The objective of this study therefore is to determine some characteristics of the watershed by using GIS approach with a view to model the water resources utilization of the catchment.

2. Description of the Study Area

The area of study is the catchment of a concrete dam built across Odomu River between Idofian and Elerinjare with N08°, 26.658’; E040°, 40.556’ coordinates (Figure 1). The dam was built with the purpose of serving NCAM, Idofian and Elerinjare communities with potable water in mind.
3. Materials and Methods

3.1 Study catchment and characteristics

3.1.1 Catchment boundary delineation. The perimeter of the catchment was delineated with the aid of a Global Positioning System (GPS) using the co-ordinate of the concrete dam located at Elerinjare and some software such as Google Earth. This was carried out to obtain the catchment boundary as shown in figure 2 below. The catchment is made up of eight villages, namely Okanle, Amodu-Asungbolu, Fajeromi, Okanle, Arugbo, Irapa, Basanyin villages; names of three others yet to be discovered. The major river, Odomu river dammed at Elerinjare with its tributaries is as shown in the catchment.
3.1.2 Generation of Topographical Map

The topographical map of the catchment was generated with the use of GPS, Arc GIS and Google Earth. The contours were generated from DEM using ArcGIS as shown below:

3.1.3 Catchment characteristics.

Determination of the following catchment characteristics for the catchment was carried out: Catchment (or river basin) has certain characteristics; these characteristics vary with respect to geological time, and are therefore considered constant. Some of these characteristics include the following:

3.1.3.1 Catchment boundary delineation.

Coordinates of the dam site were obtained using the Geographical Positioning System (GPS), the coordinates were then inputted into Google earth to locate the dam imagery, an online software that has the imagery of the entire earth. The same dam coordinate was used to determine the appropriate Shuttle Radar Topographical Mission (SRTM); SRTM consisting of an online database of the whole earth. The SRTM data was then converted into Digital Elevation Model (DEM) using ArcGIS, which was also used to delineate the catchment. Having delineated the catchment, the stream network was then digitized in DEM; a process known as draping.

(i) Basin Area: This can be defined as the area of the closed curve which is obtained by projecting the catchment boundary on to a horizontal plane, usually determined by planimetering from reasonably large scale maps, expressed in square kilometers. The area of a basin increases as the outlet point shifts downstream (Reddy, 2008). The Basin Area of this catchment was determined using ArcGIS = 6,111,547.45 m$^2$ = 61.115 km$^2$

(ii) Stream Order: This a classification that reflects the degree of branching or bifurcation at the stream channels within a basin. Assuming a channel network map of a basin, the smallest fingertip tributaries are
given the order 1; the stream order continues to increase as streams of same order combines within the catchment (Reddy, [8] 2008) i.e. orders 2, 3, 4, etc. The measurements of the stream lengths were carried out after digitization of the catchment; the measurement tool in ArcGIS was used to measure it directly (Figure 3).

**Figure 3** Catchment showing the Mainstream and its tributaries

(iii) Drainage density: refers to the ratio of the total length of streams of all orders within the catchment to the basin area; i.e. \( D_d = \frac{\sum L}{A} \)  

The implication of a low drainage density is poor drainage conditions in the watershed. Higher drainage densities are expected where the soils are easily eroded, or relatively impermeable, with steep slopes and scanty vegetation. Drainage density also enhances the evaluation of overland flow within the basin. The average length of overland flow within the basin equals half the reciprocal of the drainage density; i.e. \( \bar{L}_o = \frac{1}{2D_d} \)  

Drainage density for the catchment = \( D_d = \frac{40.105}{61.115} \) /km  

Average length of overland flow for catchment, \( \bar{L}_o = \frac{1}{2D_d} \)  

(iv) Stream density: also known as stream frequency refers to the ratio of the number of streams (Ns) to the Basin area (A). Therefore, for the catchment,
\[ D_n = \frac{N_x}{A} \quad (4) \]

\[ \frac{15}{\pi^{1/3}} = 0.245/km^2 \]

(v) Length: Catchment length refers to the length, measured along the main stream from the catchment outlet to the remotest part of the catchment boundary. The main stream in a catchment is determined by starting at the outlet and following the stream of the highest order.

The catchment length for the catchment under consideration = 13.598 km

(vi) Basin shape

Basin shape is quantitatively determined by factors such as form factor, circulatory ratio, elongation ratio and compactness coefficient (Reddy, 2008).

(a) Form factor

\[ \text{Form factor} = \frac{\text{Basin Area (A)}}{\text{(Basin length)}^2} \quad (5) \]

Form factor for catchment = \[ \frac{61.115 \text{km}}{\text{(13.598)}^2} \] = 0.331

(b) Circulatory Ratio: is defined as the ratio of the basin area to the area of the circle whose perimeter equals the perimeter of the basin. The Circulatory Ratio for the catchment, therefore for the catchment,

\[ R_c = \frac{4\pi \times A}{P} \quad (6) \]

\[ \frac{4 \times 3.142 \times 61.115}{48.466} = \frac{768.963}{2388.953} = 0.327 \]

(a) Elongation Ratio: refers to the ratio of the diameter \( D_e \) of a circle whose area is the same as the area of the basin to the length of the basin;

\[ R_e = \frac{D_e}{L} = \frac{2}{L} \sqrt{\frac{A}{\pi}} \quad (7) \]

The Elongation Ratio for the catchment, \( R_e = \frac{2}{13.598} \sqrt{\frac{61.115}{3.142}} = 0.649 \)

(d) Compactness coefficient: can be defined as the ratio of the perimeter of the basin to the perimeter of the circle whose area equals the area of the basin, i.e.

\[ C_c = \frac{P}{4\pi A} \quad (8) \]

The compactness coefficient for the catchment,

\[ \frac{48.466}{\sqrt{4 \times 3.142 \times 61.115}} = 1.749/km \]

(e) Relief: Refers to the elevation difference between the basin outlet and the highest point on the basin perimeter, usually expressed in metres.

(f) Slope: There are different ways of defining the slope of a basin, i.e.

(i) The ratio of the difference between elevations of highest point on the basin perimeter and the basin outlet to the difference between the two points.

(ii) Slope can be obtained from the stream profile. Stream profile refers to a graph representing the horizontal distance along the mainstream versus the elevation. Therefore the slope can be taken as the total fall between the end points of the main stream divided by the length of the main stream.
(g) Area-Length relation: Data obtained from a number of larger rivers all over the world were used to arrive at an Area-Length relation that allows the determination of a catchment area, knowing the length of the main stream in kilometer; i.e.

\[ L = 1.273A^{0.6} \]

(9) (Reddy, 2008)

Where

\[ L = \text{the main channel length in km} \]
\[ A = \text{the area of the basin in km}^2 \]

The equation above suggests that a basin tends to elongate as it grows longer.

The Area-Length relation for the catchment, given \( L \) as

\[ L = 1.27 (61.115)^{0.6} = 14.98 \text{ km} \]

4. Results and Discussion

The delineated area of the watershed is estimated as 61.115 km\(^2\), it was found to enclose some rural communities such as Arugbo, Amodu Asungbolu, igberi, Okanle, Basanyin, Fajeromi and Irapa. Similarly, the total length of the watershed was also found to be 13.598 km, while the elongation ratio was found to be 0.649. All these are reflections of the shape of the watershed and an indication of a long time of travel, concentration time, lag time and long flood peak.

The stream frequency of the catchment was found to be 0.245/ km\(^2\); this is a measure of the number of rivers within a unit area of the watershed. The stream frequency found to be 0.245 shows that there is a good number of rivers within the catchment for the drainage of the watershed. It is a measure of the potential to effectively evacuate generated runoff as fast as possible. The value shows a fairly efficient water evacuation process away from the catchment. This is also corroborated by the drainage density of 0.656; both characteristics indicate good drainage of the catchment and a very low likelihood of flooding.

The circulatory ratio, found to be 0.327 signifies a non-circular shape of the watershed with implication on watershed behaviours such as longer time of travel, concentration-time and time-lag. The shape of the catchment also influences the shape of the hydrograph. The shape indices considered in this study indicate that the watershed is of a non-circular shape. The compaction coefficient for the watershed is 1.749/km, which is an indication of the nature of the surface. It informs of the likelihood of the catchment being highly compacted; this suggests low soil permeability of the catchment soil as well as possible fast flood peaks.

5. Conclusion

Gross scarcity of data has often made government planning efforts to fail [1]: Furthermore, the unavailability of flow data or the use of disjointed data has also affected the quality and execution of several hydrology-related projects in Nigeria. As a result of this water resources research and development efforts in Nigeria will have to depend largely on analyzing basin variables and the use of simple coefficients in order to provide hydrologic explanations. In addition, analysis of drainage basin characteristics could offer alternative opportunity which some level of planning and project execution could be based. The results obtained from this research work will be used, using Soil and Water Assessment Tool (SWAT) to model the catchment for optimum utilization of the water resources.

References
[1] Fatokun I P and Bayode E N 2012 Watershed characteristics and their implication for hydrologic response in the Upper Sokoto Basin, Nigeria. *Journal of Geography and Geology* **4** 2

[2] Sivapalan M 2003 Process complexity at hillslope scale, process simplicity at the watershed scale: is there a connection? *Hydrological Processes* **17** 5 1037–41.

[3] Rodriguez-Iturbe I and Escobar L A 1982 The dependence of drainage density on climate and geomorphology. *Hydrological Sciences Journal* **27** 2 129-37

[4] Yildz O 2004 An investigation of the sheet of drainage density on hydrologic response. Turkish Journal of Engineering and Environmental Sciences, **28** 85-94

[5] Sreenivasulu V and Bhaskar P U 2010 Estimation of catchment characteristics using remote sensing and GIS techniques. *International Journal of Engineering Sciences and Technology* **2** 12 7763-70

[6] Sule B F, Olla O O and Adeniran K A 2009 Improvement of water supply to the National Centres for Agricultural Mechanization, Ilorin, Kwara state, Nigeria. *Journal of Research Information in Civil Engineering* **6** 1 16-25

[7] Olla O O 2007 Design of a water distribution network for the National Center for Agricultural Mechanization (NCAM), Ilorin, kwara state (2007). Unpublished M. Eng. Thesis, Department of Agricultural and Biosystems Engineering, University of Ilorin, Ilorin, Nigeria

[8] Reddy P J R 2008 A textbook of hydrology, published by University Science Press, India