Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2022, 10, 299-312
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Influence of the Geomorphology of the Okpara Watershed on Lowland Water Resources (Benin)

Idrissou Sinabarigui[1], O. Luc Sintondji[1], Mathieu Hounsou[1], Jean-Pierre Vandervaere[2]

[1]Laboratory of Hydraulics and Water Management (LHME), National Water Institute, University of Abomey-Calavi, Abomey-Calavi, Benin
[2]Institute of Environmental Geosciences, PHYREV Team, Grenoble Alpes University, PhITEM (Physics, Engineering, Earth, Environment, Mechanics), Grenoble, France
Email: idrissinabarigui@gmail.com

How to cite this paper: Sinabarigui, I., Sintondji, O. L., Hounsou, M., & Vandervaere, J.-P. (2022). Influence of the Geomorphology of the Okpara Watershed on Lowland Water Resources (Benin). *Journal of Geoscience and Environment Protection, 10,* 299-312.
https://doi.org/10.4236/gep.2022.1012017

Received: August 24, 2022
Accepted: December 26, 2022
Published: December 29, 2022

Abstract

Inland valleys are agro-ecosystems whose study is necessary not only for agricultural and agro-pastoral perspectives but also for the management of natural crises such as floods and droughts. This cannot be done by ignoring the catchment area which circumscribes them. The present study aims at evaluating the geomorphological parameters of the basin and their influence on the hydrological functioning of the Okpara catchment in general and the lowlands in particular for a good management of the said basin. To do so, an SRTM image was exploited thanks to GIS and Remote Sensing tools to analyze the morphometric properties of this watershed with ArcGIS 10.3 software. Through the results of this study, it can be seen that the Okpara watershed is very elongated, the relief is not very uneven with a dense hydrographic network characterized by low peak flood flows. The watershed is characterized by a permeable geological formation that favours a good infiltration of surface water and limits runoff. Thus, for a good management of the catchment area from these lowlands at the head of the hydrographic network, it is important to undertake actions to improve the storage capacity and to restore the flow channels.

Keywords

GIS, DEM, Hydrology, Morphometry, Watershed, Okpara

1. Introduction

Inland valleys are important for food security and income, through market gardening and rice cultivation, but also because of their role in livestock, fishing and wood production. This multifunctionality of the lowland gives it a place of choice in densely populated Sudanian areas, when we know that in addition to demographic pressure, there are water constraints, floods, submersions, erosion, droughts, growing land insecurity and environmental risks (Serpantié et al., 2019).

Agriculture, dominated by food crops constitutes the main source of income for most of the population of the Okpara basin. It occupies an average about 66% of the working population (Desaintmartin, 2017) with an estimated population of 1,174,331 in 2013 (INSAE, 2003). There is therefore a great threat to the water supply and food needs of the populations of this basin especially as new food habits are emerging with urbanization. Also, major hazards and potential impacts are identified in this area. These are rainfall extremes, change in agricultural seasons, early/late cessation of rainfall, reduction/increase in rainfall totals, pockets of drought, floods, increase in temperature and evapotranspiration (Akponikpe et al., 2019). But what about the influence of the morphometric characteristics of the Okpara watershed on its hydrological functioning? The study of geomorphological and hydrological aspects is necessary for a good management of the watershed/lowland complex of the area.

It is in this logic of work that this general evaluation of the influence of the morphometric characteristics on the flow of water for a good management of the Okpara catchment area fits. More specifically, the aim is to determine the morphometric and hydrographic characteristics of the basin and then to evaluate their influence on the water resource.

2. Methodology

2.1. Presentation of the Study Area

Located in the West African zone, Benin is watered by a fairly dense hydrographic network with the Ouémé River (510 km) and its tributaries, including the Okpara on the left bank, as its main watercourse. It has its source in Pèrèrè, precisely in Daroukpara, and flows into the Ouémé in the village Okpa. Its approximate length is 362 kilometres. The Okpara sub-basin which is the subject of this study has a surface area of about 9405 km^2, of which 6 748 km^2 are in Benin and a perimeter of 829.37 km. It is located between 8˚13' and 10˚03' North latitude and between 2˚31' and 3˚25' East longitude and covers the departments of Collines and Borgou in Benin. Several communes are drained by the waters of this basin, namely Bembèrèkè, N'Dali, Nikki, Pèrèrè and Parakou in the North of the basin and Tchaourou, Ouèssè and Savè in the South of the basin. **Figure 1** shows the location of this basin.

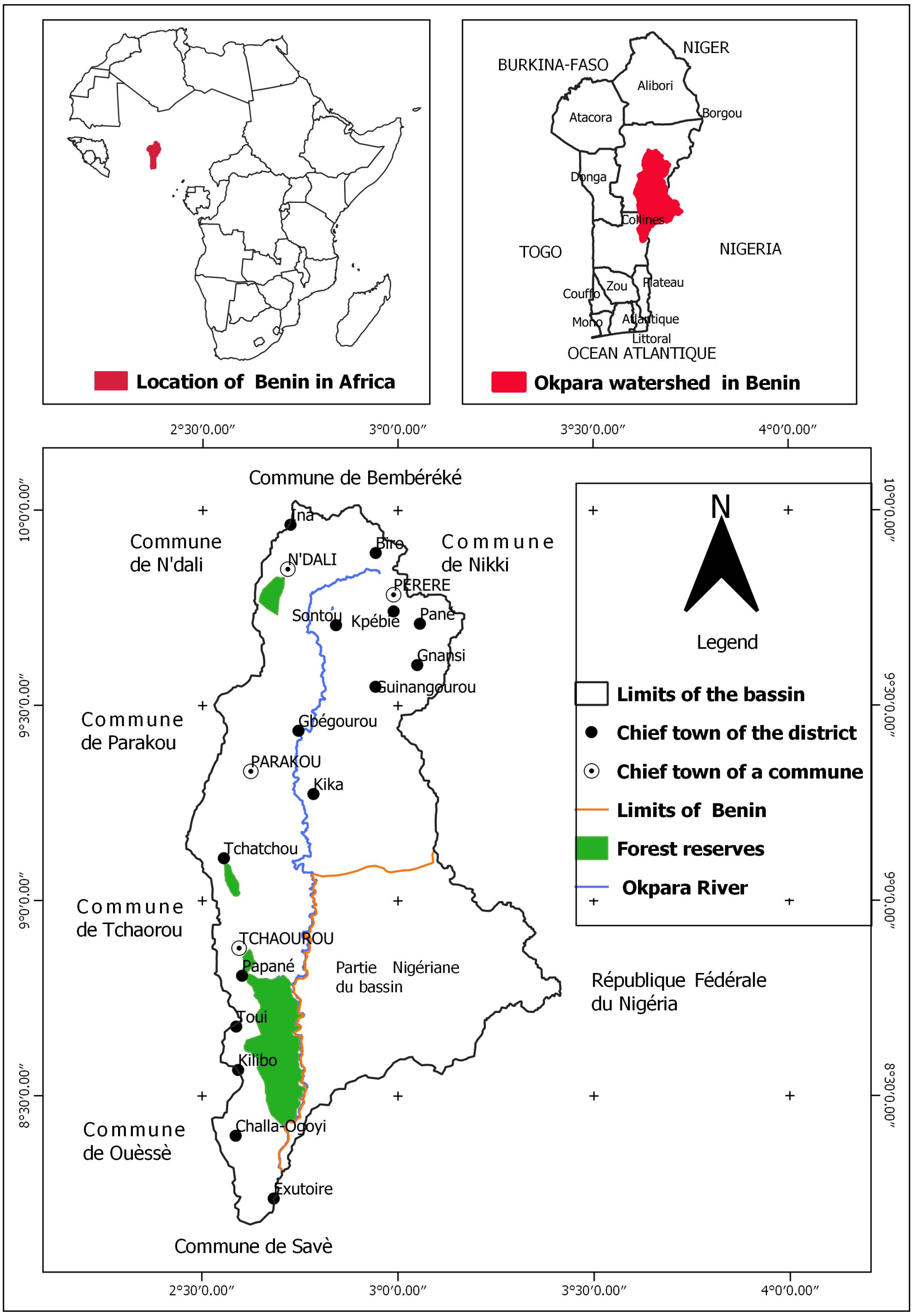

Figure 1. Location of the Okpara catchment.

➢ Climate

The Okpara basin is under the influence of the tropical Sudanian climate in its northern part and the sub-equatorial climate in its southern part. The bimodal rainfall regime in the South is fading to become unimodal. It is marked by a 7-month rainy season that extends from mid-April to mid-November and a 5-month dry season that extends from mid-November to mid-April. September is the wettest month in the Savè region (south) with an average rainfall of 171.91 mm, while the wettest months in the Parakou region (north) are August and September with average rainfall of 219.12 and 219.3 mm respectively. Temperatures are relatively higher in Savè than in Parakou, with values ranging from 25.62 in August to 31˚C in March in Savè and from 25.17 in August to 30.61˚C in March in Parakou (Météo-Bénin, 2020). August appears to be the wettest month and January the driest month at both stations.

➢ **Soil**

Located on the crystalline basement, the soils of the Okpara to Kaboua watershed are very varied in terms of their nature and geographical distribution. The tropical ferruginous soils best characterize the basin. Three groups of these soils can be distinguished: impoverished tropical ferruginous soils, leached tropical ferruginous soils and leached tropical ferruginous soils with concretions. Tropical ferruginous soils are of average or poor fertility at the surface and low at the infiltration horizon. They are followed by alluvial soils or raw mineral soils from deposits left by the Okpara River and its tributaries at the bottom of the valleys. Other types of soils are also observed in the basin, but not very evolved. These are hydromorphic soils found at the bottom of the valleys and on the porphyritic granite, quartzite and colluvial sediment peneplains. Ferralitic soils are very little represented.

2.2. Data and Materials

The data and materials used are as follows:

- An SRTM Digital Elevation Model with a 30 m resolution that can be downloaded from the website http://earthexplorer.usgs.gov/;
- 1000 points of IGN geodetic marker elevation values from https://geobenin.bj/fr/;
- ArcGIS 10.3 and QGIS 3.8 software to produce the maps and generate the morphometric parameters of the watershed;
- The SWAT model "Land and Water Assessment Tool" coupled with ArcGIS geographic information systems software for the delimitation of the Okpara basin;
- Excel 2016 for the calculation of some parameters and the realization of the graphs.

2.3. Data Processing

2.3.1. Digital Elevation Model (DEM) Validation Method

Digital Elevation Model is a very important material in this study. It is used to determine all the topographic features of the watershed, the extraction of the hydrographic network and its characteristics. The DEM used here is the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m from http://earthexplorer.usgs.gov. To be useful for a particular application, a DEM must be sufficiently accurate (Hengl & Reuter, 2008). To judge the quality of the DEM, a check of the accuracy in altimetry of the quality of the DEM data in the study area was done using 1000 points of the IGN geodetic marker elevation values from https://geobenin.bj/fr/. The verification consists in determining the error of the elevation, this error is defined as the difference between the DEM values and the elevation values of the IGN geodetic markers. Different criteria such as the coefficient of determination R^2, the RMSE normalization criterion (RSR) (Moriasi et al., 2007) defined by:

$$\text{RSR} = \frac{\text{RMSE}}{\sigma z} \rightarrow \text{RSR} = \sqrt{\frac{\sum_{i=0}\left(Z_{-\text{MNT}} - Z_{-\text{IGN}}\right)^2}{\sum_{i=0}^{n}\left(Z_{-\text{MNT}} - \overline{Z_{-\text{MNT}}}\right)^2}} \quad (1)$$

and the root mean square error (RMSE) (Mhamad, 2013 in Chritian, 2019) defined by:

$$\text{EMQ} = \text{RSME} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(z_{-\text{MNT}} - z_{-\text{IGN}}\right)^2} \quad (2)$$

were used to assess this error. The coefficient of determination of the DEM being close to 1, the selection is made on the three other criteria. Considering the RSR coefficient, the SRTM is the one that best fits the values of the geodetic boundary heights (RSR close to zero). To confirm the choice, the root mean square error is used. The most commonly used statistical descriptor to evaluate a DEM is the root mean square error. If the value of the RMSE is small, then the DEM is considered accurate (Mhamad, 2013 in Chritian, 2019). **Figure 2** and **Table 1** show the correlation plot of geodetic boundary heights with SRTM heights and DEM validation parameters respectively.

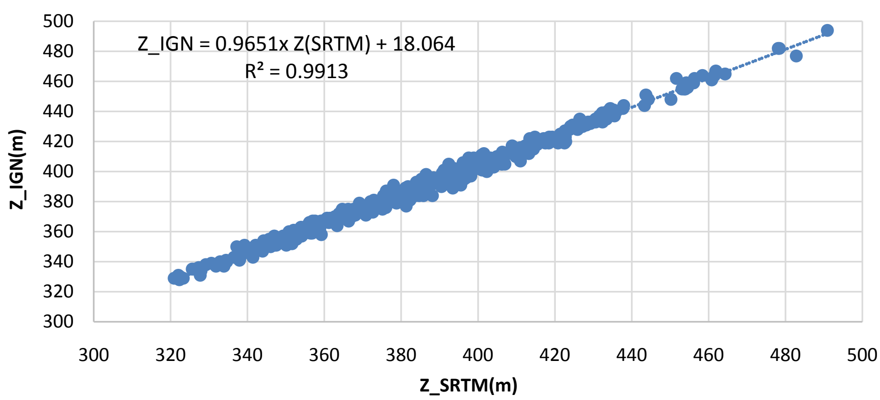

Figure 2. Correlation of geodetic monument heights with SRTM heights.

This figure shows the good correlation between the points of the IGN-Benin geodetic markers and the altitudes extracted from the DEM used.

Table 1. DEM validation parameters.

Validation parameters	SRTM (N06_e002)
The coefficient of determination R^2	0.9913
RSR	0.17
EMQ	5.58

The values of the various parameters for assessing the quality of the SRTM confirm the low altitude error and therefore the good quality and reliability of the DEM. The SRTM (N06_e002) is therefore suitable for our various operations.

2.3.2. Determination of the Morphometric Characteristics of the Basin

- **Watershed area and perimeter**

They were obtained from ArcGIS 10.3 software after delineating the watershed.

- **Compactness index**

The Gravelius (1914 in Sabi Zingui, 2019) compactness index is defined as the ratio of the perimeter of the basin to the perimeter of the circle having the same area. The formula is:

$$k_G = \frac{P}{2\sqrt{\pi S}} \tag{3}$$

P: Basin perimeter; S: Basin area (Table 2)

Table 2. Classification of the Gravelius compactness index (ORSTOM, 1966).

Catchment area	Surfaces	Form
B5	$1.7 \le K_G$	Very elongated
B4	$1.4 \le K_G < 1.7$	Extended
B3	$1.3 \le K_G < 1.4$	Amoeboid
B2	$1.03 \le K_G < 1.3$	Ovoid
B1	$1 \le K_G < 1.03$	Circular

Source: Konin et al. (2021).

- **Length (L) of the equivalent rectangle**

The notion of the dimension of the equivalent rectangle was obtained by the formula:

$$L = \frac{k_G \times \sqrt{\pi S}}{2}\left(1 + \sqrt{1 - \left(\frac{2}{\sqrt{\pi} \times k_G}\right)^2}\right) \tag{4}$$

- **Relief**

The relief plays an important role in the hydrological behaviour of the catchment area through the slope which influences the flow speed, the water concentration time and the infiltration rate. The influence of the relief on the flow is easily conceived, because, many hydrometeorological parameters vary with the altitude (precipitations, temperatures, etc.) and the morphology of the basin.

The hypsometric curve represents the distribution of the surface of the watershed according to its altitude. There are four types of characteristic elevations that can be calculated from the hypsometric curve:

- **Average altitude**

It can be deduced directly from the hypsometric curve or from a topographic map. It can be defined as follows:

$$H_{moy} = \sum \frac{A_i \times h_i}{A} \tag{5}$$

with H_{moy}: average altitude of the basin [m]; A_i: area between two contour lines [km^2]; h_i: average altitude between two contour lines [m]; A: total surface area of the catchment area [km^2].

Median altitude

The median elevation is the elevation read at the point with an abscissa of 50% of the total area of the basin on the hypsometric curve. This value is close to the mean altitude if the hypsometric curve of the basin concerned has a regular slope.

Maximum and minimum altitude

They are obtained directly from Digital Elevation Models using ArcGIS 10.3 software. The maximum elevation represents the highest point in the basin while the minimum elevation is the lowest point generally at the outlet.

➢ **Average slope of the watershed**

The average slope gives a good indication of the travel time of the runoff and therefore of the concentration time and directly influences the peak flow during a rainfall. Several methods have been developed to estimate the average slope of a basin. All of them are based on a reading of a real or approximate topographic map or from a DEM. In this study, we adopted the method proposed by Carlier and Leclerc (1964 in Nadjla, 2006). It consists in calculating the weighted average of the slopes of all the elementary surfaces included between two given altitudes. An approximate value of the average slope is then given by the following relation:

$$Im = \frac{L \times D}{A} \tag{7}$$

where Im: average slope [m/km or 0/00]; L: total length of contours [km]; D: equidistance between two contours [m] and A: catchment area [km^2].

➢ **Elevation gain**

The difference in height D is calculated from the Excel software by the following formula:

$$D = \mathrm{H5\%} - \mathrm{H95\%} \tag{8}$$

where H5% and H95% are the altitudes obtained from the hypsometric curve by taking the points such that the upper or lower surface is equal to 5%.

➢ **Overall slope index**

The overall slope index was calculated from the formula:

$$IG = \frac{D}{L} \tag{9}$$

where D: height difference (m) and L: length of the equivalent rectangle (km).

➢ **Specific gradient (Table 3)**

The specific gradient is used for watershed classification and is calculated using the following formula:

$$DS = IG\sqrt{A} \tag{10}$$

Table 3. Relief classification based on specific altitude difference (ORSTOM).

Class	Type of relief	Ds
R1	Very low relief	$Ds < 10$ m
R2	Low relief	$10 < Ds < 25$ m
R3	Fairly low relief	$25 < Ds < 50$ m
R4	Moderate relief	$50 < Ds < 100$ m
R5	Fairly strong relief	$100 < Ds < 250$ m
R6	Strong relief	$250 < Ds < 500$ m
R7	Very strong relief	500 m $< Ds$

Source: Sabi Zingui (2019).

2.3.3. Study of the Hydrographic Network

➢ **Length of stream**

A watershed is characterized primarily by the length of the main stream (LT), which is the curvilinear distance from the outlet to the drainage divide, always following the higher order segment when there is a branch. If the two segments at the junction are of the same order, the segment with the larger drainage area is followed.

➢ **Average slope of stream**

The average slope of a river determines the speed with which water reaches the outlet of the basin and therefore the time of concentration. This variable influences the maximum flow observed. A steep slope favours and accelerates surface runoff, while a gentle or zero slope gives the water time to infiltrate fully or partially into the ground. Average stream slopes are calculated from the longitudinal profile of the main stream and its tributaries. The most common method of calculating longitudinal stream slope is to divide the difference in elevation between the extreme points of the profile by the total length of the stream.

$$P_{moy} = \frac{\Delta H_{\max}}{L_T} \quad (11)$$

where:

P_{moy}: average stream slope [m/km]; $\Delta H_{\max}$: maximum river gradient [m]; L_T: length of main stream [km].

➢ **Drainage density**

The drainage density introduced by Horton is the total length of the drainage network per unit area of the watershed:

$$Dd = \frac{\sum L_i}{A} \quad (12)$$

with:

Dd: drainage density [km/km^2]; L_i: length of stream [km]; A: surface area of catchment area [km²].

The drainage density depends on the geology (structure and lithology), the topographical characteristics of the catchment area and to some extent on the climatological and anthropic conditions. In practice, the values of the drainage density vary from 3 to 4 for areas where the flow has only reached a very limited development and is centralized; they exceed 1000 for certain areas where the flow is very branched with little infiltration. According to Schumm (1956), the inverse value of the drainage density $C = 1/Dd$ is called the "stream stability constant". Physically it represents the area of the basin required to maintain stable hydrological conditions in a unit hydrographic vector (section of the network). Schumm (1956) classified the stability constant (km²/km) into five different categories, namely: more erodible (<0.2), moderately erodible (0.2 to 0.3), moderately poorly erodible (0.3 to 0.4), poorly erodible (0.4 to 0.5) and less erodible (>0.5).

- **Hydrographic Density**

The hydrographic density represents the number of rivers per unit area.

$$F = \frac{\sum N_i}{A} \tag{13}$$

where F: hydrographic density [km^{-2}]; N_i: number of rivers and A: surface area of the basin [km²].

- **Bifurcation ratio**

The confluence ratio expresses the development of the drainage network. It varies according to the order considered. It is an important element to consider when establishing correlations from one region to another. According to Adhikari (2020), the bifurcation ratio ranging between 3 and 5 indicate the natural drainage system within a homogenous rock. The lower value of bifurcation ratio are characteristics of the watershed which have flat or rolling watersheds while the higher values of bifurcation ratio indicate strong structural control on the drainage pattern and have well-dissected drainage basins.

$$R_c = \frac{Nu}{N(u+1)} \tag{14}$$

where Nu: Number of streams of order "u"; $N(u + 1)$: Number of next order streams; U: Order of a stream; "u" varies between 1 and w (w is the order of the main stream *Strahler* classification).

- **Stream frequency**

It represents the ratio of the number of first-order streams to the area of the watershed under study.

- **Torrentiality coefficient**

It is the ratio between the frequency of first-order streams and the drainage density. It reflects the aggressiveness of the downpours in the catchment area; the greater the value of the coefficient, the greater the torrentiality.

$$C_T = Dd \times F \tag{15}$$

3. Results and Discussions

3.1. Geomorphological Characteristics of the Okpara Watershed in Kaboua

Table 4. Characteristics of the Okpara watershed in Kaboua.

Parameters	Symbol	Unit	Value
Length of the equivalent rectangle	*L*	km	389.63
Perimeter	*P*	km	829.4
Area	*A*	Km^2	9406
Compactness index	K_G		2.4
Overall slope index	*IG*	m/km	0.38
Elevation gain	*D*	m	150
Specific gradient	*DS*	m	37.34
Average watershed slope index	*Im*	m/km	40.36

The analysis of Table 4 shows that with a GRAVELIUS coefficient equal to 2.4, the Okpara watershed has a very elongated shape (as shown in Table 2), which favours low peak flood flows, due to the longer time it takes for the water to reach the outlet. Its average slope is 40.36 m/km or 4%. This implies that the slope of this basin is low. The global index of slope (IG) which is 0.38 is characteristic of a strong relief according to the classification of the ORSTOM while the specific difference in level (*Ds*) is 37.34 m. This indicates that the relief is of type R3 (as shown in Table 3) and therefore rather weak and exposed to water erosion.

3.2. Hydrological Curve of the Watershed

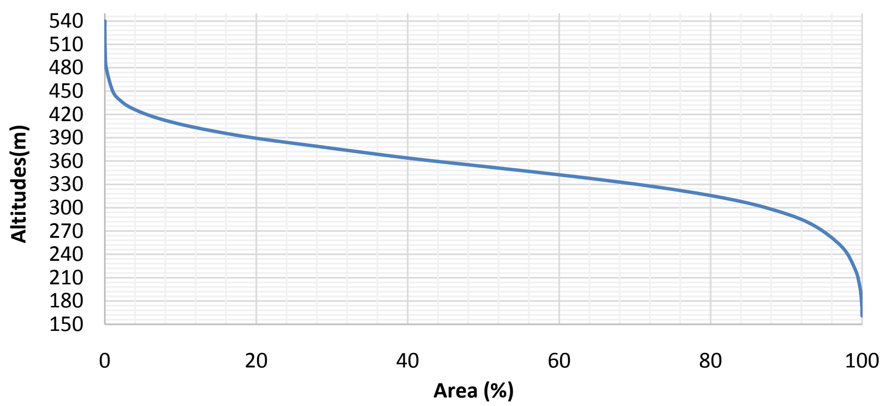

Figure 3. Hypsometric curve of the Okpara basin at Kaboua.

The hypsometric curve of the Okpara catchment (Figure 3) reflects the shape of the slopes and their distribution in altitude. This curve shows a strong slope in the high altitudes and a weak slope towards the low altitudes. Its shape indicates that the Okpara to Kaboua watershed is in a mature state. From this curve, the following altitudes were determined:

- The maximum altitude of 540 m correspond to the top of the watershed;
- The minimum altitude (outlet) of 161 m;
- The median altitude corresponding to a cumulative surface of 50% is equal to 355 m;
- The average altitude is 351.85 m calculated according to formula (6);
- The 5% altitude is 420 m;
- The 95% altitude is 270 m.

This altitudinal distribution of the basin relief has a direct influence on its hydrological regime and on the whole erosive dynamics (Boudjadja & Khaled, 2018).

3.3. Hierarchy of the Hydrographic Network of the Okpara

From the analysis of **Figure 4**, the hydrographic network of the Okpara watershed according to *Strahler*'s system is of order 8. This indicates that this network is old, because it is quite branched and influenced by the abundance of rainfall and the slope of the land (Strahler, 1975 in Sabi Zingui, 2019). **Table 5** below summarizes the different parameters that characterize the Okpara watershed network.

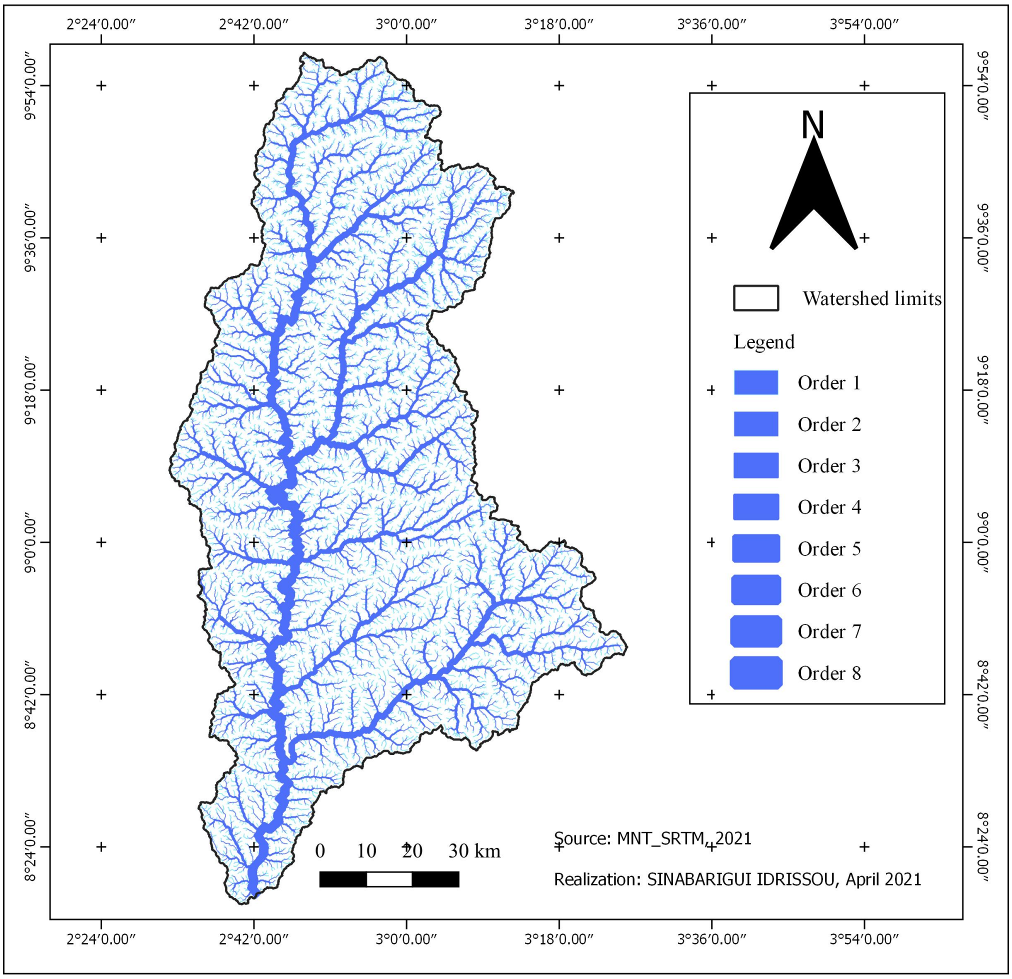

Figure 4. Stream ordering of the river basin according to Strahler.

Table 5. Hydrographic characteristics of the Okpara watershed.

Parameters	Symbols	Units	Values
Length Talweg	*LT*	km	275
Length of the network	*Li*	km	12390
Drainage density	*Dd*	Km/km^2	1.3
Stream stability constant	*C*	Km^2/km	0.76
Hydrographic Density	*F*	Km^{-2}	2.3
Average slope of stream		m/km	1.37
Stream frequency		Km^{-2}	3.54
Torrentiality coefficient	*Ct*	Km/km^4	2.23
Classification of the hydrographic network	-	-	8
Bifurcation ratio	*Rc*		1.3 à 2.5

From the analysis of **Table 4** and **Table 5**, we note that the average slope of the watercourse (1.76 m/km) is low, thus giving the water time to infiltrate entirely or partially. The low drainage density ($Dd = 1.3$ Km/km^2) reveals that the basin as a whole presents a permeable geological formation with limited flow and high infiltration (Strahler, 1957). Hydrographic density, which often goes hand in hand with drainage density, indicates slower runoff and flooding in the watershed. It also characterizes an area of highly permeable bedrock with significant vegetation cover and rugged terrain. The torrentiality coefficient ($Ct = 2.23$ km/km^4) shows that this watershed has a coarse type of drainage (Faye et al., 2021) and does not have morphometric characteristics adapted to the flow. The value of the bifurcation ratio varies from 1.3 to 2.3 depending on the order of the streams considered, this indicates that the geology of the Okpara to Kaboua watershed strongly influences the flow (Adhikari, 2020). The length of the main stream and the drainage network indicate that the watershed is quite branched, which influences the flow of water at the outlet. But the low value of the stability constant of the rivers (0.76 Km^2/km) allows us to say that the watershed is less erodible (Schumm, 1956). This has a strong influence on the availability of water resources in this sub-catchment of the Ouémé River.

4. Conclusion

GIS and remote sensing tools are used in this study to assess the morphometric and hydrographic characteristics of the Okpara catchment. This study reveals that the Okpara watershed is very elongated in shape according to the GRAVELIUS coefficient. This favours low peak flood flows due to the long time, it takes for water to reach the outlet. The time of concentration is then high. The total length of the hydrographic network and that of the main river indicate that this watershed is quite branched, which influences the flow of water to the outlet. The altitudinal distribution of the relief (hypsometric curve) of the basin has a direct influence on its hydrological regime and on the overall erosive dynamics.

The overall slope index and specific gradient are characteristic of a strong relief and also show that this basin is exposed to water erosion. The overall slope index and specific gradient are characteristic of strong relief and show that this basin is exposed to water erosion. The average slope of stream being low gives time for water to infiltrate entirely or partially. The low drainage density and hydrography reflect that the basin has a permeable geological formation with limited flow. The value of the torrentiality coefficient confirms the presence of this geological formation and also shows that the Okpara watershed does not have morphometric characteristics adapted to the flow. In view of all these results, it would be good to consider actions to improve water storage capacity, rehabilitation and restoration of drainage channels, especially at the head of the hydrographic network.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Adhikari, S. (2020). Morphometric Analysis of a Drainage Basin: A Study of Ghatganga River, Bajhang District, Nepal. *The Geographic Base, 7,* 127-144. https://doi.org/10.3126/tgb.v7i0.34280

Akponikpe, P. B. I., Tovihoudji, P., Lokonon, B., Kpadonou, E., Amegnaglo, J., Segnon, A. C., Yegbemey, R., Hounsou, M., Wabi, M., Totin, E., Fandohan-Bonou, A., Dossa, E., Ahoyo, N., Laourou, D., & Aho, N. (2019). *Etude de Vulnérabilité aux changements climatiques du Secteur Agriculture au Bénin.* Report Produced under the Project "Projet d'Appui Scientifique aux processus de Plans Nationaux d'Adaptation dans les pays francophones les moins avancés d'Afrique subsaharienne". Climate Analytics gGmbH.

Boudjadja, C., & Khaled, L. (2018). *Caractérisation géomorphologique et morphométrique et impact sur l'érosion du bassin versant de l'Oued Boussiaba (Wilaya de Jijel)* (96 p.). Université de Jijel.

Chritian, A. K. (2019). *Modélisation hydrodynamique de l'aquifère du continental terminal du champ de captage de Ouedo: Quelques options de conditions aux limites* (82 p.). MSc. Thesis, University of Abomey-Calavi.

Desaintmartin, E. (2017). *Diagnostic Agropastoral et transition agro-écologique de la zone cotonnière du Bénin: Cas de trois terroirs villageois de la région de Parakou* (90 p.). MSc. Thesis, Ecole Supérieure d'Agro-Développement International.

Faye, C., Dièye, S., & Faye, G. (2021). Analyse morphométrique et hydrologique du sous-bassin versant du Niaoule (bassin de la Gambie) a l'aide de techniques SIG. *Algerian Journal of Arid Environment, 11,* 54-77.

Hengl, T, & Reuter, H. I. (Eds.) (2008). *Geomorphometry: Concepts, Software, Applications* (Vol. 33, pp 1-89).

INSAE (2003). *Troisième recensement général de la population et de l'habitation, Synthèse des résultats* (34 p.). Direction des études démographiques Cotonou.

Konin, N. J. C., N'Go, Y. A., Soro, G. E., Ya, K. F., & Goula, B. T. A. (2021). Influence des facteurs hydro-morphostructuraux sur les inondations du bassin versant du fleuve

San-Pedro, Côte d'Ivoire. *Revue Ivoirienne des Sciences et Technologie, 37,* 106-122. http://www.revist.ci

Météo-Bénin (2020). *Base de données de l'Agence Nationale de la Météorologie du Bénin.*

Moriasi, D. N., Arnold, J. G., Van Liew, M. W. et al. (2007) Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE, 50,* 885-900. https://doi.org/10.13031/2013.23153

Nadjla, B. (2006). *Utilisation d'un SIG pour l'évaluation des caractéristiques physiques d'un bassin versant et leurs influences sur l'écoulement des eaux (bassin versant d'Oued El Maleh, Nord-Ouest d'Algérie).* Conférence Francophone ESRI 11 et 12 octobre, SIG 2006.

Sabi Zingui, R. (2019). *Apports de la télédétection et des systèmes d'information géographique dans la modélisation hydrologique d'un bassin versant: Cas du Mékrou à Koupoungou (Bénin)* (101 p.). MSc. Thesis, University of Abomey-Calavi.

Schumm, S. A. (1956). Evolution of Drainage System and Slope in Badlands of Perth Amboy, New Jersey. *Geological Society of America Bulletin, 67,* 597-646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

Serpantié, G. et al. (2019). Nouveaux risques dans les bas-fonds des terroirs soudaniens. Une étude de cas au Burkina Faso. *Cahiers Agricultures, 28,* Article No. 19. https://doi.org/10.1051/cagri/2019020

Strahler, A. N. (1957). Quantitative Analysis of Watershed Geometry. *Eos, Transactions American Geophysical Union, 38,* 913-920. https://doi.org/10.1029/TR038i006p00913