Riverine Hydrokinetic Energy Potential in Selected Rivers In North Central, Nigeria

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Abstract

This work technically assesses Nigeria's hydrokinetic energy potential with the view to developing an indigenous technology, based on the peculiar hydrology of Nigerian rivers, as a national renewable energy resource. The research team focused on the main rivers in the southern River Niger basin in the North-central region of Nigeria for a start. The methodology was to first obtain the aggregate theoretical hydrokinetic power available in the rivers and then determine the recoverable (technically obtainable) resource. The first involves using a hydrological model and spatial tool while the other is through field measurements and analysis. A hydrological model using the GIS system MapWindow, was used to simulate the hydrological parameters of the sub-basins and computation was also made using a spreadsheet software package to estimate the instantaneous power that can be obtained along the river stretch. The technically recoverable hydrokinetic power potential was computed by allocating a recovery factor to each river subdivision in the database and summing the product of the recovery factor and the theoretical resource across the subdivisions. Results show there are potentials of this technology in the investigated southern River Niger basin. The total estimated value of the theoretical resource for the watershed totals 826.7 MW while the estimated value for the technically recoverable resource totals 198.4 MW. River Awun has the highest technically recoverable hydrokinetic power potential of 257.5 MW while River Oshin has the lowest (20.9 MW).

Keywords: *Energy, GIS, Hydrology, Microhydro, River Niger*

INTRODUCTION

Hydrokinetic (in-stream, or water current) energy conversion implies the utilization of the kinetic energy of watercourses, rivers, tidal currents or other man-made water channels for the generation of electricity. It is an emerging variant of the Small Hydropower (SHP) technology and a class of "zero head" hydropower. Unlike traditional hydropower, which entails the use of hydraulic head and water discharge to generate power, hydrokinetic technology apply the energy in the velocity of the water to turn turbines. This technology provides an innovative approach of exploiting the SHP potentials of various local water bodies without the financial and environmental effects of constructing dams. The way it works is similar to that of wind turbine technology, though energy is tapped through hydrodynamic, rather than aerodynamic, lift or drag (Khan *et al.,* 2007). The available electrical power that can be mined from a hydrokinetic system depends on the density of the water, the cross sectional area of the flowing water channel or the swept area of the turbine and the velocity of the water current. The smallest workable range of velocity for the technology is between 1.03 ms^{-1} and 2.06 ms^{-1} (ACEP, 2011).

In recent times, there has been an upsurge of interest in the technology in various parts of the world and developments have been made on various aspects of the technology ranging from resource assessment to turbine design and modelling (Bane *et al*, 2017; Holanda *et al*, 2017; Nzualo, 2017; Poidexter, 2018; NRC-CHC, 2010; Khan *et al.,* 2009). Natural Resources Canada (2008) developed a method to identify potential locations where hydraulic kinetic energy turbines could be installed using the data available at the watershed scale in Canadian rivers. In Brazil, South America, Tiago (2013) demonstrated the generation of AC power directly using small axial flow and cross flow turbines. Using ducts, the system was able to power a remote medical post in the State of Bahia. Also in Argentina, a channelling device was used with a vertical axis turbine and tests were carried out on it (Ponta and Dutt, 2000). The tests were able to improve the power output. The hydrokinetic resource potential in the United States was also estimated by Miller *et al.* (1986). The total resource potential was computed by assuming some turbine parameters and this provided a conservative resource estimate of 12.5 GW. Mapping and assessment of hydrokinetic resources in rivers of the continental United States was also done by the Electric Power Research Institute (EPRI). It was found that these undeveloped resources could deliver 3 % of the nation's annual electricity utilised (EPRI, 2012). Ladokun *et al.* (2014) also investigated the prospects and challenges of this technology in Nigeria and proffered frameworks for its adaption to Nigeria's energy mix.

Nigeria has a huge potential of small, mini and micro scale hydropower, which can be tapped and converted to useful energy and supplied to serve thousands of communities in urban, semi-urban and rural areas as well as locations that are off-grid. The National Centre for Hydropower Research and Development (NACHRED) under the Energy Commission of Nigeria, as part of her mandate, has identified the need to assess Nigeria's hydrokinetic potential. This is with the view to developing an indigenous technology, based on the peculiar hydrology of Nigerian rivers, as a national renewable energy resource. The research team's focus was on the major rivers in the Lower Niger River Basin in North Central Nigeria namely Awun, Oshin, Moshi, Ero and Oyi for a start. These rivers are assessed based on their gross naturally occurring energy potential and based on the technically recoverable resource.

The assessment of resource potential has long-term benefits of building non-commercial knowledge to support both government and industry and assist in the development of hydrokinetic resources. For industry, knowledge of the potential and where it is located are key pieces of information for early marketing of the technology to developers and funding agencies. Government requires reliable technical information as output of research efforts for policy and decision-making. It will also benefit remote regions where decentralized power production from renewable energy sources can be an economically viable option compared to the high cost of diesel/petrol power production.

METHODOLOGY

2.1 Study Area: Lower River Niger Watershed

The southern basin of River Niger is located in the north-central Nigeria between Latitude 9.55^{0}N, Longitude 3.13^{0}E and Latitude 8.52^{0}N, Longitude 6.52^{0}E. It has River Niger as its northern border, Benin Republic on the west, on the east, the Benue River basins and on the south by the Ogun-Oshun River basin. It spreads out with an estimated area of 48,600 km^2 and a perimeter of about 998 km. It is situated between Hydrological Zone II and III of Nigeria. The watershed has River Niger as the major river passing through it and some major tributaries. Some of the major tributaries are: Rivers Awun, Moshi, Oshin, Oyi and Ero. Automatic delineation of the Digital Elevation Model (DEM) of the watershed gives 131 sub-basins and 181 Hydraulic Response Units (HRUs). River networks in the watershed and topographical layout are presented in **Figures 1 and 2**. The climate of the study area is that of the tropical savanna, which corresponds to Koppen classification A_W (Elmhurst College, 2014). These climates have an elaborate dry season, with little or no precipitation during the harmattan, while the rainy season does not produce as much rains as the tropical rainforest, which operates in the southern regions. Rainfall totals around central Nigeria, where lies the basin, varies from 1,100 mm in the lowlands to over 2,000 mm in the highlands. Minimum temperatures are usually around 18 °C (64 °F) and this occurs in January and December. The harmattan season is between December and March while the rainy season occurs between April and November. Notable towns and villages within the basin area are Ajase-Ipo, Ilorin, Ejiba, Bode-Saadu, Olooru, Moshi-gada, Lafiagi and Kpada.

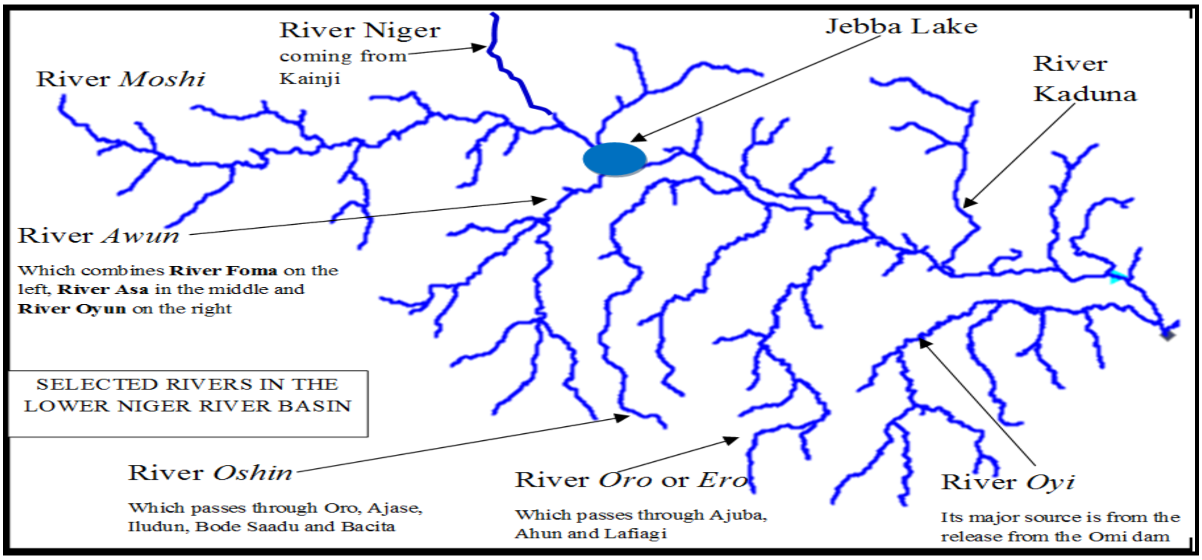

Figure 1: Stream networks of the Lower River Niger Basin

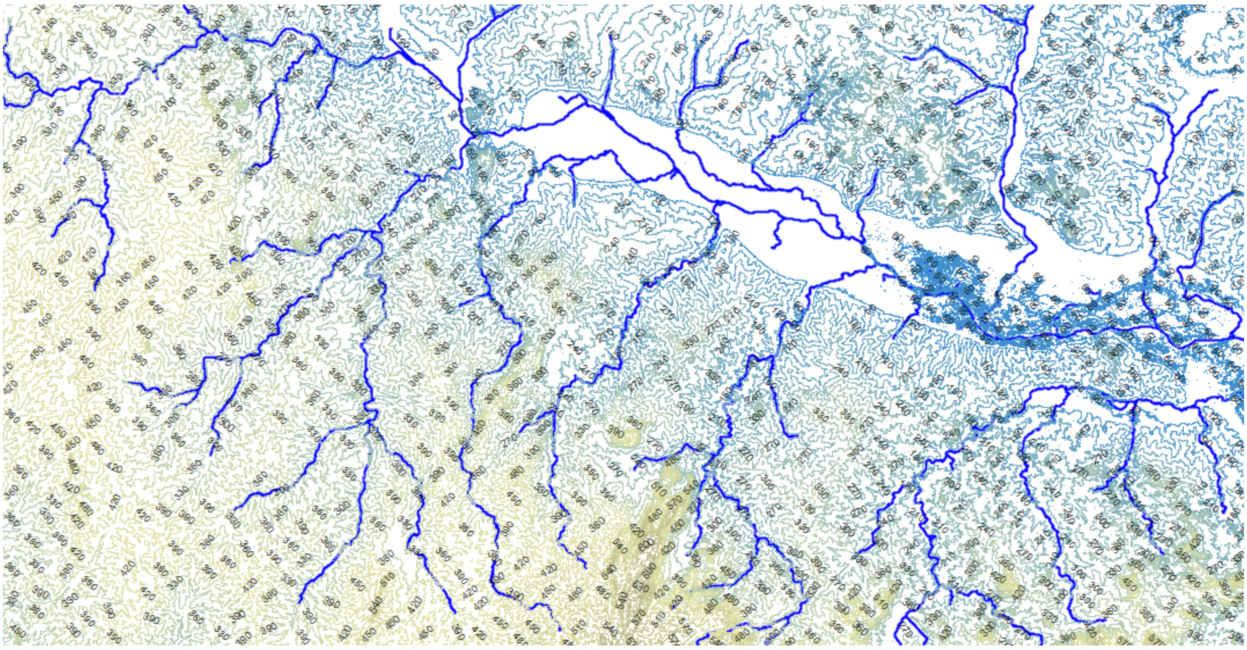

Figure 2: Stream networks of the rivers in the watershed and its topography

2.2 Use of Hydrological Model and Spatial Tool

The technique used in this work involves obtaining the gross naturally occurring theoretical hydrokinetic potential of the rivers to determine the recoverable (technically obtainable) resource. The first step involves the use of a hydrological model and spatial tool while the other is through field measurements and analysis.

2.2.1 Theoretical Hydrokinetic Energy Potential

The theoretical energy resource can be said to be the segment specific gross naturally available hydrokinetic resource of the watershed. It is the average annual energy available for hydrokinetic technology. The theoretically available hydrokinetic power in a given river division P_{th} (Watts) is given as in Eq. 1:

$$P_{th} = \gamma Q \Delta H \qquad (1)$$

Q is the specific average water discharge in each division (Q) with units of cubic meters per second. Hydraulic head (ΔH) is computed from divisional length and slope.
γ refers to the specific weight of water (9800 N m^{-3}).

MapWindow Soil and Water Assessment Tool, MWSWAT, which is an open source linked display to the Soil and Water Assessment Tool, SWAT using the GIS system MapWindow, was used for modelling to determine the hydrological parameters of the sub-basins. This is a catchment-scale continuous time model that operates on a daily time step with up to monthly or annual output frequency. The process was initiated by taking all input data **(Table 1**) and setting them to the same projection. Then the catchment area was divided into sub-catchments using the Automatic Watershed Delineation component. Each sub-catchment was connected through a river channel and further divided into Hydrologic Response Units (HRU).

The HRU is a unique combination of a soil and vegetation types within the sub-catchment. The model calculations were performed on HRU basis and flow and water quality variables were routed from HRU to sub-basin and subsequently to the watershed outlet. **Figures 3, 4 and 5** show the delineation into sub-basins, the HRUs and the combination of the sub-basins and the HRUs respectively. After the GIS processing, the input files were configured and then simulated using SWAT. Weather values were drawn from their sources in the SWAT database. For the initial run of the model, simulation period was set from 01 January 2000 to December 31, 2010.

Table 1: Modeling Input data, their sources and resolution

Data Type	Description	Resolution	Source	Remark
Topographical Map	Digital Elevation Model (DEM)	90m × 90m	SRTM	Shuttle Radar Topographical Mission
Land Use Map	Land Use Classification	1km	GLCC	Global Land Cover Classification Satellite Raster
Soil Map	Soil Types and Texture	10km	FAO	Digital Soil Map of the World
Weather	Daily Precipitation, Minimum and Maximum Temperatures, Relative Humidity, Wind, Solar radiation		NIMET, Jebba and Kainji Hydropower Stations	

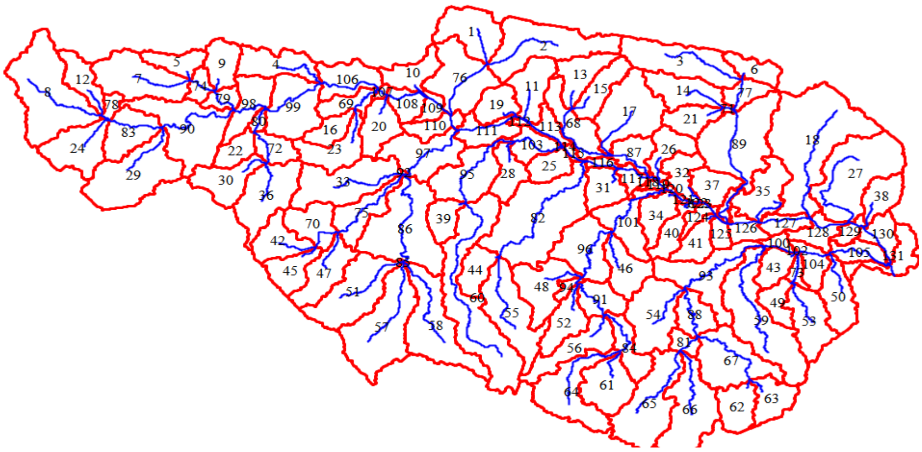

Figure 3: Demarcation of Study Area into Sub basins

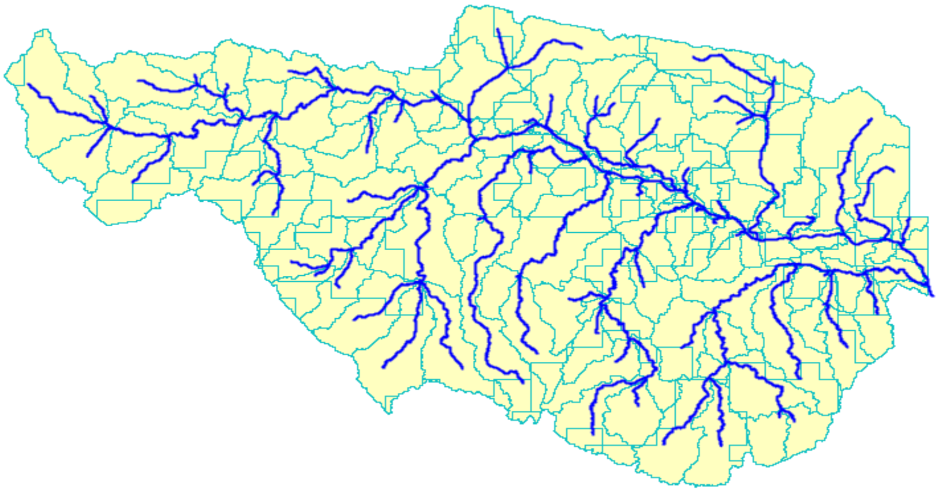

Figure 4: Subdividing into Hydrological Response Units

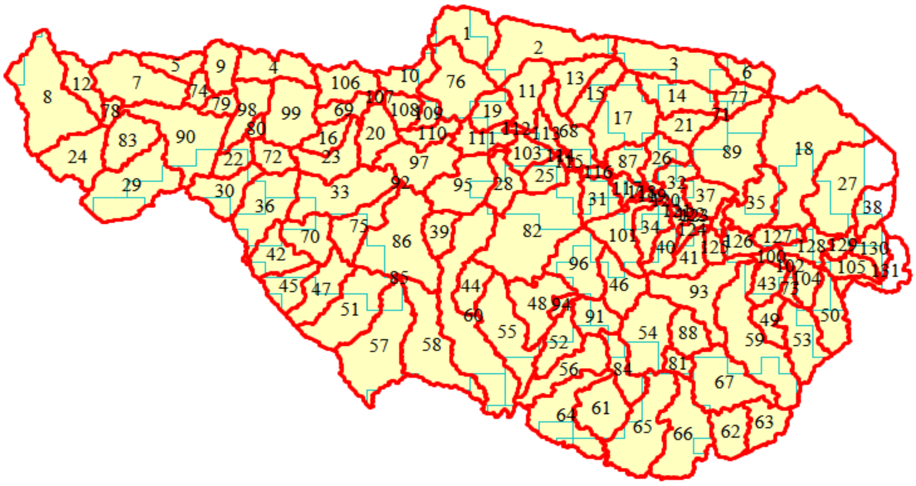

Figure 5: Watershed showing the different sub basins and HRUs

2.2.2 Technically Obtainable Hydrokinetic Energy Potential

The technically obtainable hydrokinetic power in a given river division can be defined as the quantity of power that could be obtained given contemporary technologies. It reduces the amount of the theoretical resource as a result of some technical limitations and assumptions. Estimation of the technically obtainable resource follows the expression in Eq. 2.

$$P = \frac{1}{2}\rho\, \mathrm{U}_o{}^3\, \eta CpNA_t \qquad (2)$$

where P denotes the recoverable power, A denotes cross-sectional area of the river segment or swept area of the turbine, ρ denotes water density, and U_o denotes velocity magnitude, ηCp is the product of the efficiency and the power coefficient and N is the number of turbines in the river segment. Obtaining the technically available resource involves much field work to obtain actual hydrologic/hydraulic parameters. Ten sites (Table 3) were focused on the five selected major rivers based on reconnaissance surveys during the early rainy period, study of satellite imageries, availability of river gauging stations and information from local residents. They are:

(i) River Oshin at: Oro and Bode Saadu in Kwara State
(ii) River Oro at: Ajuba in Osi LGA and Lafiagi in Kwara State.
(iii) River Moshi at: Moshi-gada and Maje village in Kwara State
(iv) River Oyi at: Ejiba in Kogi State and Kpada in Kwara State
(v) River Awun at: Olooru and Aderan in Kwara State.

Field surveys and measurements were done to obtain the stage, bathymetry and cross-sectional area of some parts of the river. Flood rating curves and flow duration curves were developed for some sites using the available data.

Table 3: Selected Rivers, their Location and their Gauging points

River	**Gauging Point**	**Location**	**Length of Record, Years**
Oshin	Oro	8°13' N and 4°53'E	1984– 2009 (≈20yrs)
Oshin	Bode Saadu	8°56' N and 4°46'E	*1984 – 2009 (≈20 yrs)
Oro	Ajuba	8° 05'N and 5°23' E	2010 – 2014 (≈4 yrs)
Oro	Lafiagi	8° 50'N and 5° 25' E	2013 – 2014 (≈2 yrs)
Moshi	Moshi-gada	9^0 12’N and 3^0 51’E	2010 – 2013 (≈3 yrs)
Moshi	Maje	9^0 09’ N and 4^0 26’E	*2010 – 2013 (≈3 yrs)
Oyi	Ejiba	8^0 18’ N and 5^0 37’ E	2010-2013 (≈3.5 yrs)
Oyi	Kpada	8^0 36’ N and 6^0 05’ E	*2010-2013 (≈3.5 yrs)
Awun	Olooru	8^0 38” N and 4^0 34’ E	2011 – 2013 (≈2.5 yrs)
Awun	Aderan	9^0 03’ N and 4^0 45’ E	*2011 – 2013 (≈2.5 yrs)

- Due to insufficient and unavailable data for some remote locations, secondary data were used

Figure 6 (a)-(f) show gauging activities in some selected sites across the watershed area.

(a) (b) (c) (d) (e) (f)

Figure 6: (a) River Awun at Olooru (b) River Moshi at Maje (c) River Moshi at Moshi-gada (d) River Oshin at Oro (e) River Ero at Lafiagi (f) River Oyi at Ejiba

Numerous measurements of stream discharge were made over a range of stream stages. These were utilized for determination of the hydrokinetic power estimates of each site. A scalar factor called ***recoverable factor,*** which is a function of the river slope and average discharge, was then evaluated. Evaluation involves the use of Manning's Eq. 3 and the hydrokinetic flow Eq. 2.

$$V = {}^{1}/_{n}\, R^{2/3} S^{1/2} \tag{3}$$

where V represents the average flow velocity, R represents the hydraulic radius, N represents the roughness, S represents the water slope for uniform flow conditions.

Inputs from the MWSWAT attribute table and the table of estimated values of river bottom roughness (Chow, 1959) was used to determine the average velocity of the channel at free flow *v*. The total annual recoverable hydrokinetic power potential for the river at a particular slope and the technically recoverable resource was then obtained. Using the recovery factor R_{f1}, the estimates of the annual total recoverable hydrokinetic resource for the total channel area was determined.

3.0 RESULTS AND DISCUSSION

3.1 Preliminary Simulation Results

MWSWAT output can be visualized by making a results shape file showing the sub basins of the watershed, and then the SWAT outputs are displayed by colouring the sub basins according to the values generated by the output. This involves making the output values an attribute of the shape file. **Figure 8** presents the maximum discharge inflowing each sub basin.

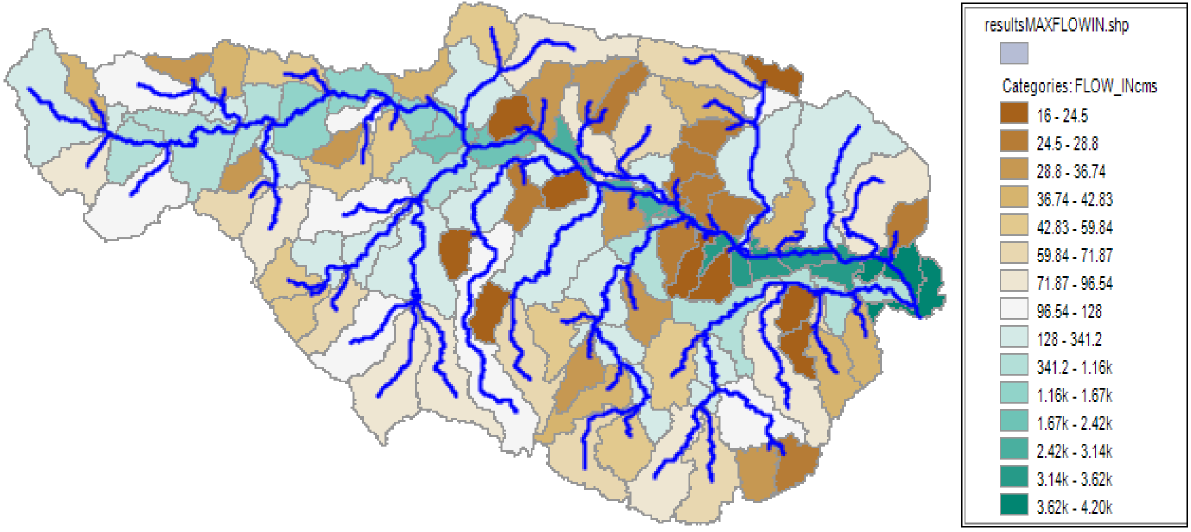

Figure 8: **Maximum discharge flowing into the Sub basins**

The output of the computed average annual flow moving into and leaving each sub basin is presented in **Figures 9 and 10** respectively.

3.1 The Theoretically Obtainable Hydrokinetic Energy Resource Potential

The values of the theoretical resource for the southern River Niger basin and its rivers are computed using the hydraulic Equation (1). The hydraulic variables of the river sites; the slope, straight L, and ΔH were obtained. The estimated average annual flow and their corresponding mean hydrokinetic potential were also calculated using spreadsheet software. Preliminary results show that Awun at sub-basin code 97 has the highest potential. Aderan community, off Jebba road is situated in the sub-basin. Sub-basin code 91 also has the highest potential along River Ero. Ahun near Oro-Ago town is situated there. Sub-basin code 107 holds the highest potential for the river Moshi followed by sub-basin code 106. Maje is in that sub-basin. The 93rd sub-basin holds the highest potential in Oyi River.

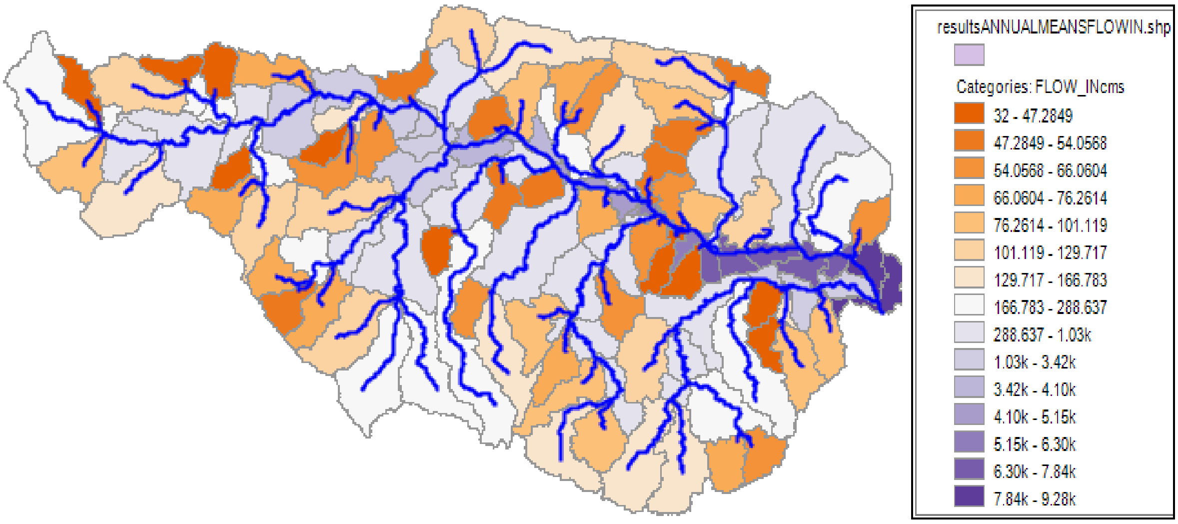

Figure 9: **Mean annual flow into the sub basins**

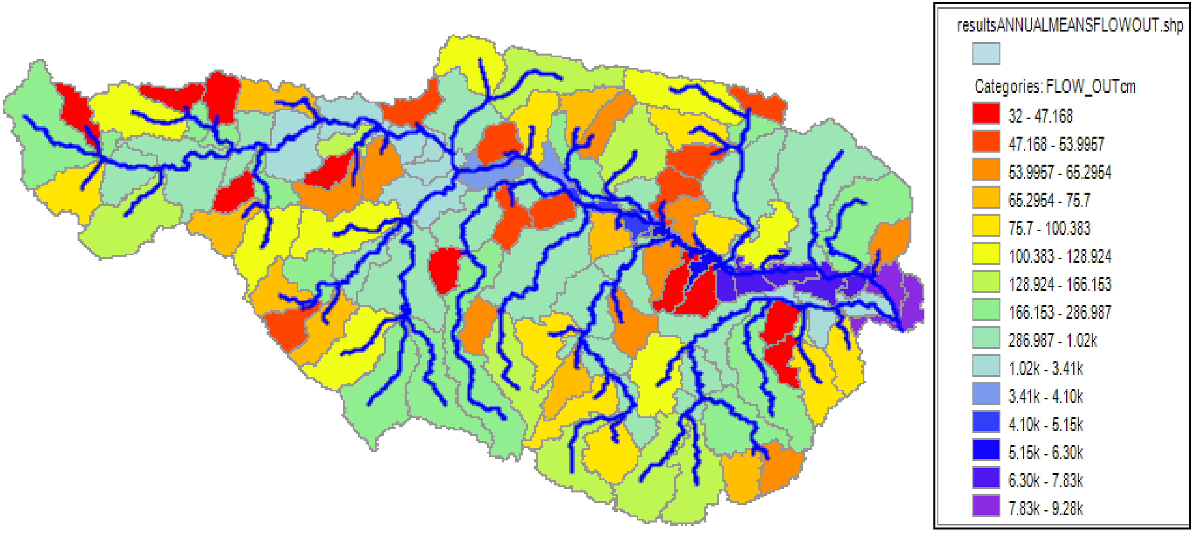

Figure 10: **Mean annual flow departing the sub basins**

Kpada (a town in Kwara State) and Ejiba (in Kogi state) also have significant hydrokinetic potential along the river. Along River Oshin, sub-basin 103, which is downstream Jebba, holds the highest potential. Oshin site along Bacita road is accessible and has good hydrokinetic potentials too.

Table 2 presents the estimate of the theoretical hydrokinetic power resource (average daily) for the southern River Niger sub-basin. **Figure 11** shows the mean annual hydrokinetic power potential that can be obtained along the sub basins.

Table 2: **Rivers, their Mean Discharge and the Theoretical Hydrokinetic Potential**

S/N	**Rivers**	**Average Discharge (m^3/secs)**	**Theoretical Hydrokinetic Resource (Average Daily MW)**
1	Moshi	8315.78	6.190
2	Awun	2438.01	8.466
3	Oyi	6644.93	6.110
4	Oshin	1224.27	0.688
5	Oro	2887.28	5.737
TOTAL			**27.191**

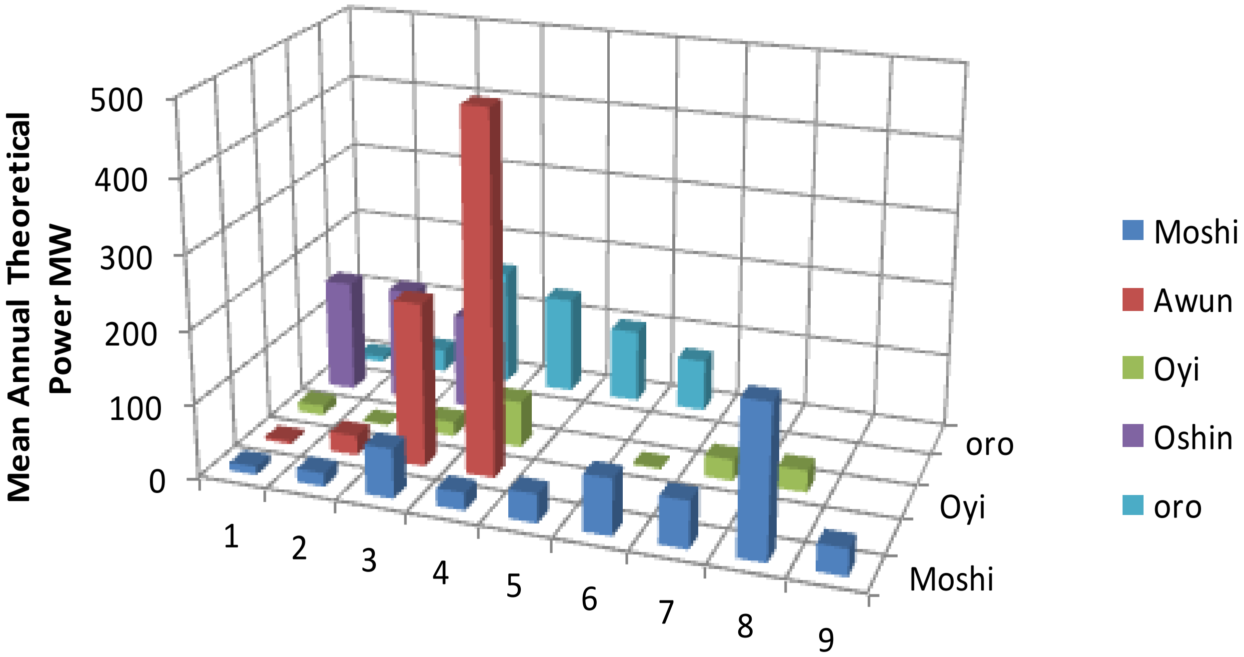

Figure 11: **The Theoretical Hydrokinetic Power Potential along the Sub Basins**

3.2 The Technically Obtainable Hydrokinetic Energy Resource Potential

Application of the procedure in the flowchart (**Figure 7)** on the major rivers in the sub-basin gives the recovery factors shown in **Table 4** and the technically recoverable hydrokinetic power potential presented in **Table 5**. **Figure 12** presents the chart showing the technically recoverable hydrokinetic power across the sub-basins.

Table 4: Selected Channels and their Computed Recovery Factors Rf_1

Rivers	Mean Velocity (m/s)	Area (m^2)	Discharge (m^3/sec)	Computed Recovery Factors
Awun	1.54	39.72	61.17	0.003728
Oshin	1.51	17.52	26.50	0.027721
Moshi	1.79	16.93	30.31	0.018980
Ero	1.68	63.21	106.25	0.055300
Oyi	1.50	57.67	86.59	0.128900

Table 5: Rivers and the Technically Recoverable Hydrokinetic Resource

Rivers	Total Average Discharge (m^3/secs)	Technically Available Hydrokinetic Resource (Average Daily MW)
Awun	61.17	1.493
Oshin	26.50	0.099
Moshi	30.31	1.115
Ero	106.25	0.852
Oyi	86.59	1.101
	TOTAL	**4.660**

The theoretical hydrokinetic power resource potential for the watershed totals 27.2 MW i.e. 0.2384 TWh yr^{-1}. River Moshi has the maximum theoretical discharge (8315.78 m^3 $secs^{-1}$), while River Oshin has the lowest (1224.27 m^3 $secs^{-1}$). Also, River Awun has the highest theoretical hydrokinetic potential of 8.466 MW while River Oshin has the lowest (0.688 MW). The estimate of the technically obtainable hydrokinetic resource for the watershed totals 4.660 MW i.e. 0.04085 TWh yr^{-1}. Again, River Awun has the peak technically obtainable hydrokinetic resource potential of 1.493 MW while Oshin has the lowest (0.099 MW).

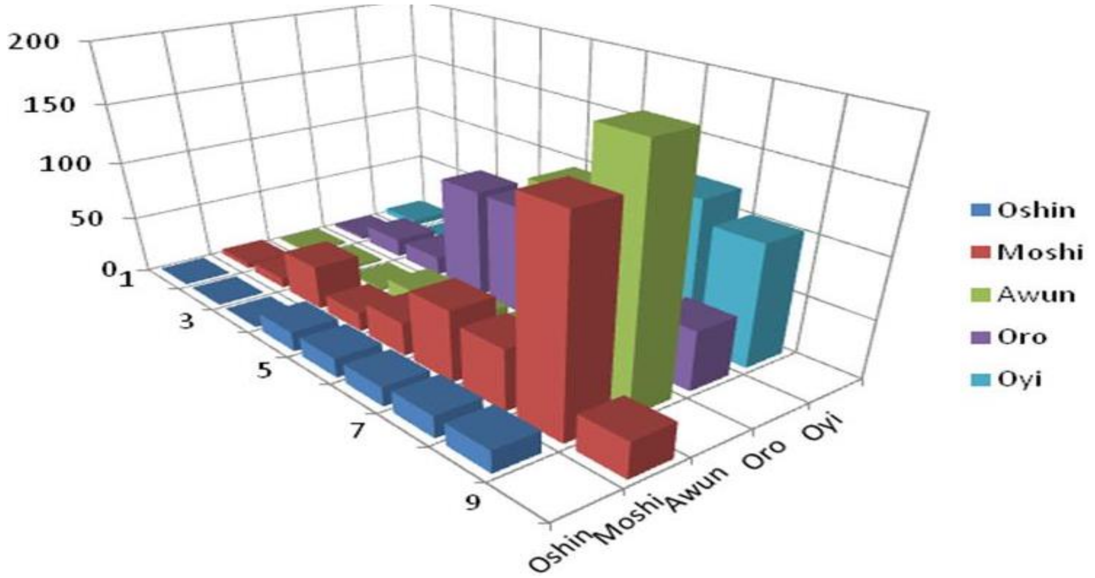

Figure 12: **Chart showing the Technically Recoverable Hydrokinetic Potential across the Sub-basin**

4.0 CONCLUSION

Regional assessment of the potential for hydrokinetic power has been carried out for the southern basin of River Niger to obtain the gross theoretical hydrokinetic resource and the technically recoverable power potential. Feasible rivers and river sites where hydrokinetic power can be developed in the southern basin of River Niger were determined. Results show there are naturally occurring potentials of this technology in the Niger River watershed.

Further works in water kinetic energy resource assessment shall evaluate the spread of technically obtainable hydrokinetic resource across the range of flows at all sites. Large annual and inter annual variation in flow makes this particularly essential. Additional works are also still to be done for assessment of the feasible, available and achievable hydrokinetic power in the region.

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