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Analysis of Flow Variability in Otamiri River, Imo State, Nigeria

*** Ibeje, A.O.**

Department of Civil Engineering, Imo State University, PMB 2000, Owerri, Nigeria.
*engineeribeje@gmail.com

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ABSTRACT

Flow duration curve (FDC) is widely used in hydrology to assess the flow regime of a river. This paper presents the derivation of FDC for Otamiri catchment in Imo State, Nigeria. FDC was constructed from 1979-1989 mean monthly flow data, ranked from largest to smallest value, with each corresponding percentage of months for which the flow value was equaled or exceeded. The flow duration curve was obtained by plotting flow versus exceedence frequency. The derived flow duration curve was used to characterize the flow in the range from 10% to 90% of time flow is equaled or exceeded. This maximum flow and average flow were determined as 9.22 m^3/s and 7.21 m^3/s respectively while the power potential and installed capacity were computed as 175.38 kW and 224. 28 KW respectively. The dependable power and average annual energy generated were estimated as 102.41 kW and 1,536,357.27 kWh respectively. The reliability of hydropower generation in Otamiri catchment can be assessed based on the lowest monthly flow which was estimated for Otamiri as 7.21 m^3/s. The design flow was estimated as 9.22 m3/s. This study has demonstrated that FDC is useful in water resource assessment of river catchments.

1. INTRODUCTION

The flow duration curve (FDC) is a graphical representation of the frequency distribution of the complete flow regime of a river (Pumo et al., 2014). A FDC is defined by Serinaldi (2011) as a function which gives flow, q, as a function of probability, p, i.e., q = q(p), where p is the probability that the specified flow is exceeded. Empirical FDCs are graphs, or alternatively tables, constructed from a set of flow measurements (q_i) made over a given interval of time, ranked from largest to smallest value, with each corresponding p giving the percentage of days for which the flow value was equaled or exceeded. In empirical FDCs, the area under the curve represents the volume of flow and the storage that will affect the FDC thereby reducing the extreme flows and increasing the very low flows. In the FDC, the shapes at the upper and lower regions are the most important parts in evaluating the characteristics of a river (Muller and Thompson, 2016). The upper-flow region indicates that the basin is likely to have flooded, whereas, the lower-flow region characterizes the ability of the basin to sustain low flows during dry seasons. A flat curve indicates a river with few floods but with large groundwater contribution, while a steep curve indicates frequent floods and dry periods with little groundwater contribution (Boscarello et al., 2016).

FDC is commonly used for resource assessments including water supply and water quality assessment and the evaluation of river habitats (Vogel and Fennessey, 1995). Duration curves for long periods of runoff are also useful for deciding the flow rates to be used for particular purposes, say, for power development (Zhang et al., 2015). Since drought is often defined in terms of a fixed period of time with less than some minimum amount of rainfall, the FDCs are useful for determining the duration of floods or droughts, the latter being of prime importance in the semi-arid regions (Muller and Thompson, 2016). FDC provides a probabilistic description of stream flow at a given location.

Due to the extensive use of FDC in hydrology, different methodologies for the derivation of FDCs at individual gauging stations or at a regional-scale have been studied. Singh (1971), Dingman (1978) and Singh et al. (2001) proposed regression equations incorporating the drainage area and elevation of the hydrological basin as input variables to establish FDC models. The soft computational techniques such as the artificial neural networks, gene expression programming and geostatistical methods were applied by Pugliese et al. (2016) and Atieh et al. (2017) in modeling FDC. Castellarin et al. (2013) reviewed the currently used procedures for deriving FDCs in data-scarce basins, with a particular focus on the reliability of such methods in different climatic contexts. Yokoo and Sivapalan (2011) disaggregated the FDCs into two components, i.e., slow FDCs and fast FDCs to develop a conceptual model to reconstruct FDCs similar to the earlier work of Muneepeerakul et al. (2010) and Botter et al. (2007). Empirical FDCs have also been represented by a parametric function which is usually a probability distribution such as the generalized Pareto distribution with three parameters (Fennessey, 1994), the Gumbel distribution (Kottegoda and Rosso, 1997), the normal distribution (Singh et al., 2001) and the two- or three-parameter log-normal distribution (Fennessey and Vogel 1990; Claps and Fiorentino, 1997). However, in the past different non-probabilistic analytical forms were made popular by Müller et al. (2014). In more recent times, other distributions have been used, such as the Kappa by Castellarin et al. (2007), the Eta Beta by Iacobellis (2008) and the Burr type XII by Ganora and Laio (2015).

Although FDC shows the percentage of time that certain values of discharge weekly, monthly or yearly were equaled or exceeded in the available number of years of record, the selection of the time interval depends on the purpose of the study. While daily flow rates of small storms are useful for the pondage studies in a runoff river power development plant, monthly flow rates for a number of years are useful in power development plants from a large storage reservoir (Cigizoglu, 2000). The longer the period of record, more accurate is the indication of the long-term yield of a stream. A better understanding of the pattern of streamflow is obtained by a monthly analysis, which has the capability of illustrating the months that contain high flows, low flows or average flows. On annual time scale, the shape of the FDC in its upper and lower regions, which has a particular importance in evaluating the stream and basin characteristics, is masked by the averaging at the annual time scale while it becomes clear when monthly streamflow data are considered (Boscarello et al., 2016). Furthermore, FDC plotted on a log-log paper provides a qualitative description of runoff variability in the stream (Atieh et al., 2015).

Otamiri River, located in Owerri, Imo state of Nigeria, is a fast-flowing river which serves as a reliable source of water supply to Owerri and its environs (Amangabara, 2015). Unfortunately, in the river, obsolete discharge data existed only for a limited period from 1979 to 1988, after which no stream gauging was done again due to faulty gauging equipment. Having explored the merits of FDC on monthly time scale and on a log-log paper, this study is focused on the derivation of FDC for River Otamiri catchment in Imo State, Nigeria. In this study, FDC for River Otamiri will be plotted on both arithmetic and log-log scale. Through this study, the reliability of River Otamiri for possible hydropower development will be ascertained.

2. MATERIALS AND METHODS

2.1. Data Collection

The little available record was only the 1979-1988 discharge data of Otamiri River (at Nekede gauging station) as the gauging equipment was reportedly faulty till date. The data was obtained from the Anambra-Imo river basin in Imo state of Nigeria, which is one of the twelve river basin development authorities (RBDAs) in Nigeria.

2.2. Study Area

The Otamiri River itself starts as a first-order stream at its source at Egbu, Owerri North L.G.A. and captures Nworie river and flows for about 30 km to confluence with the Oramiriukwa River at Emeabiam, Owerri West L.G.A. in Imo State, Nigeria. The catchment area measures about 100 square kilometer. The source of the river is located on latitude 05°26'N and on longitude 07°02'E (Ibe et al., 2003). Amangabara (2015) reported that the Otamiri River has maximum average flow of 10.7 m^3/s in the rainy season (September - October) and a minimum average flow of about 3.4 m^3/s in the dry season (November - February). The total annual discharge of the Otamiri is about 1.7×10^8 m^3, and 22 percent of this (3.74×10^7 m^3) comes from direct runoff from rainwater and constitutes the safe yield of the river.

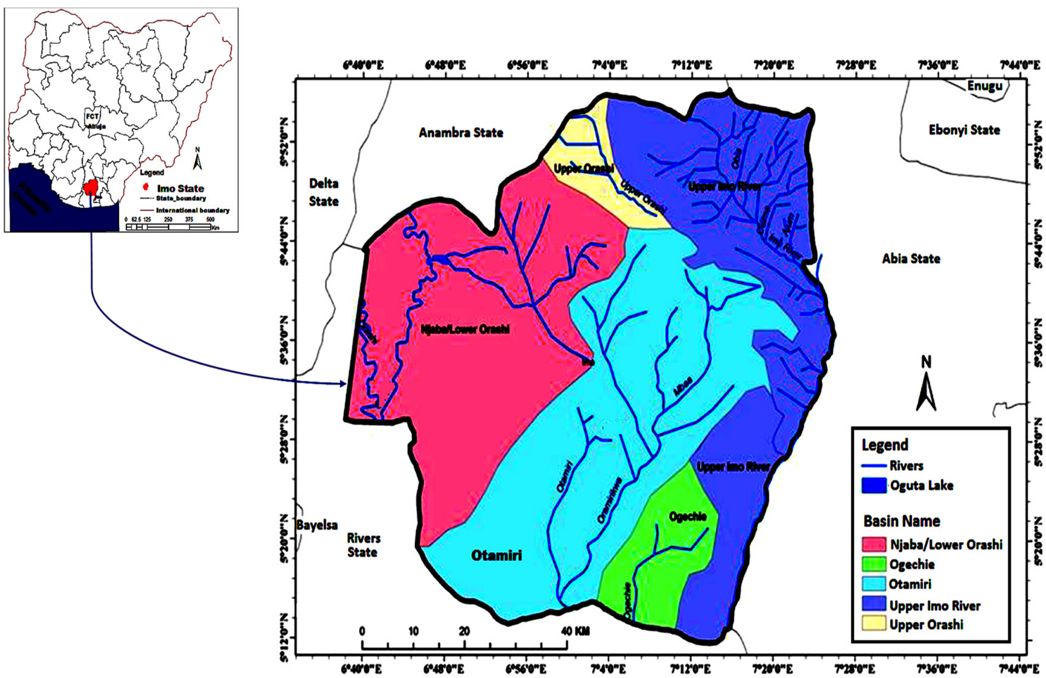

Figure 1: Otamiri sub-basin (within the five major sub-basins in Imo State) showing the location of River Otamiri (modified from Amangabara, 2015)

The 10-day average discharge data used in the evaluation of the empirical FDC of Otamiri River is shown in Table 1. Initially, the total range of discharge values (2-13 m^3/s) were divided into 12 classes of 1 m^3/s and suitable class intervals selected. The data was then scanned and the number of occurrences of each discharge value was entered into appropriate class interval and recorded and these values were then arranged in ascending order of magnitude. The number of occurrences of each discharge value was cumulative summed beginning from the last value and upwards. Thereafter, the percent of time the value of the class interval is equaled or exceeded was computed as the percent of the total number of occurrences (m) of the particular flow interval out of the 120 (=10 years ×12 months = n) called the exceedence frequency through the Weibull plotting position given by Equation 1.

$$F_m = \frac{m}{n} \times 100 \quad (1)$$

Where m is the index of the sorted value and n the total number of observations in the year of interest.

Table 1: 10-year daily average discharge data of Otamiri River

Year	Day	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
	10	3.90	3.70	3.60	3.60	3.89	4.29	7.57	7.12	6.16	4.87	4.30	3.11
1978/79	20	3.85	3.64	3.73	3.73	4.02	5.79	7.17	6.42	6.04	4.58	4.07	2.48
	30	3.8	3.60	3.96	3.96	4.35	5.96	7.67	6.19	5.24	4.50	3.80	2.27
	10	5.48	5.10	4.59	4.51	5.33	7.55	9.84	8.16	7.11	6.22	4.96	3.88
1979/80	20	5.27	4.91	4.84	4.49	5.08	8.54	10.31	7.83	6.91	6.38	4.61	3.76
	30	5.33	4.90	5.19	5.05	6.38	9.29	10.15	7.61	6.62	5.78	4.17	3.68
	10	2.68	2.31	2.41	3.67	4.03	5.14	6.06	5.96	5.85	5.80	4.80	4.41
1980/81	20	2.49	2.27	3.25	3.76	4.23	5.29	6.13	6.42	5.68	5.55	4.63	4.41
	30	2.3	2.13	3.99	4.08	4.70	5.92	6.23	6.05	5.56	5.33	4.54	4.65
	10	4.18	4.22	4.27	4.74	5.44	7.44	8.95	8.02	7.28	7.35	7.34	6.82
1981/82	20	4.23	4.23	4.57	4.88	6.26	8.62	8.67	7.67	7.24	7.43	7.09	6.92
	30	4.11	4.23	4.92	5.27	6.26	8.54	8.25	7.25	7.33	7.38	7.04	6.91
	10	6.68	6.65	7.15	6.69	6.72	7.08	7.68	7.95	8.72	8.26	7.00	7.41
1982/83	20	6.66	6.86	6.73	743	6.85	6.86	8.26	8.56	8.68	7.54	7.09	7.23
	30	6.67	7.36	6.92	6.91	7.30	7.13	8.03	8.56	8.64	7.26	7.26	7.35
	10	7.53	7.86	10.17	9.98	3.70	10.46	11.57	11.41	11.20	11.20	10.57	10.14
1983/84	20	7.36	7.75	10.18	9.97	9.83	11.50	11.74	11.36	11.18	11.17	10.35	9.04
	30	7.09	10.63	10.13	10.52	10.88	11.53	13.39	13.39	12.21	12.21	9.06	9.74
	10	5.97	6.20	6.57	7.19	7.34	7.87	7.70	8.27	8.68	8.02	7.57	7.70
1984/85	20	6.03	6.43	6.87	7.39	8.11	7.36	8.32	8.61	8.53	7.81	7.21	7.73
	30	6.18	6.40	6.98	7.41	8.15	7.41	8.27	8.71	8.26	7.64	7.66	8.01
	10	7.45	7.20	7.16	7.38	8.55	9.72	9.36	8.33	7.99	7.924	7.728	7.58
1985/86	20	7.44	7.12	7.15	7.99	8.99	9.18	9.04	8.16	7.99	8.036	7.74	7.75
	30	7.11	7.11	7.40	7.78	9.07	8.84	9.21	7.98	7.88	7.79	7.64	7.87
	10	7.95	8.26	8.90	7.62	8.33	8.55	9.31	9.25	9.13	9.10	8.76	8.60
1986/87	20	7.68	8.50	7.98	7.66	7.83	8.75	9.20	9.24	9.16	8.64	8.64	9.56
	30	7.88	9.49	7.68	8.68	8.07	8.69	9.18	9.14	9.10	9.05	8.65	8.74
	10	8.67	8.81	8.86	8.86	8.88	9.30	9.30	9.30	8.90	8.55	8.19	8.4
1987/88	20	8.60	8.82	8.65	8.71	8.30	9.43	9.05	9.32	8.82	8.41	8.078	7.90
	30	8.54	8.81	8.58	8.49	8.69	8.69	9.11	9.21	8.68	8.34	7.98	7.47

The lower value of each class interval as (y-axis,), was plotted against the percentage of time exceeded by flow as (x-axis) to obtain the flow duration curve FDC. The median flow (Q_{50}) is the discharge which is equaled or exceeded 50% of the time. The part of the curve with flows below the median flow represented low-flow conditions. Baseflow was interpreted to be significant if this part of the curve had a low slope, as this reflected continuous discharge into the stream. A steep slope suggested relatively small contributions from natural storages like groundwater to the streamflow. The ratio of the discharge which was equaled or exceeded 90% of the time, to that of 50% of the time (Q_{90}/Q_{50}) was used to indicate the proportion of streamflow contributed from groundwater storage according to the method by Nathan and McMahon (1990). Other low-flow indices include discharges that were exceeded at defined percentages of time, say 75, 90 or 95 % represented by Q_{75}, Q_{75} , Q_{95}.

2.3. Estimation of Power Potentials

The power potential P (kW), is an indication of the average hydropower production capability of a river and was computed from Equation 2.

$$P = 7Q_{av}H \quad (2)$$

Q_{av}, = average flow (m^3/s) or the mean monthly discharge data obtained by dividing the total annual discharge with the total number of years of data and H (m) is the water head at the flow inlet of the Otamiri gauging site.

The installed capacity, P_{IC}, for this river at the Otamiri gauging site was estimated on the basis of maximum flow Q_{15}, which is the flow available 15% of the time by substituting Q_{15} for Q_{av} in Equation (2) as:

$$P_{ic} = 7Q_{15}H \quad (3)$$

The firm or dependable power P_F, was estimated on the basis of Q_{90}, which is the flow available 90% the time by substituting Q_{90} for Q_{av} in Equation (2) as:

$$P_f = 7Q_{90}H \quad (4)$$

The average annual energy generated, E (KWh), from a proposed power plant was computed from Equation 5.

$$E = 7Q_{av}HP_{ic} \quad (5)$$

2.4. Estimation of Design Flow

The availability of flow is the percentage of time that flow is available for use in a year. The availability of flow therefore corresponds to their percentage exceedence. In computing the design flow, various flow values corresponding to different percentage exceedence Q_{15}, Q_{20}, Q_{30}, Q_{50}, Q_{60}, Q_{70}, Q_{80} and Q_{90} were read off the FDC to obtain the flow values. The availability of flow is the percentage of time that flow is available for use in a year. The availability of flow therefore corresponds to their percentage exceedence. The availability of each flow value was determined by selecting the percentage exceedence for that flow. These flow and availability values were then substituted in the power potential equation to obtain various power potentials. These power potentials were then substituted in the energy equation to obtain the corresponding annual energy generated. The flow that gives the maximum energy generation is the design flow (Q_d).

3. RESULTS AND DISCUSSION

3.1. Computations for Deriving River Otamiri Flow Duration Curve

Table 2 shows the division of the total range of discharge values (2-13 $m^{3/}s$) into 12 classes of 1 m^3/s and the recording of the number of occurrences of each discharge value in the appropriate class interval. Table 2 is the first step in deriving FDC of a river. The number of times and the percentages of time that the flow of each class interval has been equaled or exceeded in the period of the record are presented in Table 3.

Table 2: Arrangement of flow into class intervals

Year	2-2.99	3-3.99	4-4.99	5-5.99	6-6.99	7-7.99	8-8.99	9-99	10-10.99	11-11.99	12-12.99	13-13.99	Total
1978/79	0	15	4	8	5	4	0	0	0	0	0	0	36
1979/80	0	3	9	9	5	4	2	2	2	0	0	0	36
1980/81	7	4	1	10	5	0	0	0	0	0	0	0	36
1981/82	0	0	0	2	5	12	6	0	0	0	0	0	36
1982/83	0	0	11	0	12	16	8	0	0	0	0	0	36
1983/84	0	0	0	0	0	5	0	0	10	0	2	2	36
1984/85	0	0	0	1	8	15	12	70	0	0	0	0	36
1985/86	0	0	0	0	0	24	6	6	0	0	0	0	36
1986/87	0	0	0	0	0	8	15	13	0	0	0	0	36
1987/88	0	0	0	0	0	3	25	8	0	0	0	0	36
	7	22	34	30	40	91	74	36	12	10	2	2	360

Table 3: Flow duration analysis of 10-daily average monthly flow data for Otamiri River

S/No	10 daily average monthly flow class interval (c. i.)	No. of occurrences in 10 yr period (n)	No. of time equaled or exceeded (m)	percent of time lower value of c.i equaled or exceeded (m/n x 100%)
1	2-2.99	7	360	100
2	3-3.99	22	353	98.05
3	4-4.99	34	331	91.94
4	5-5.99	30	297	82.5
5	6-6.99	40	267	74.16
6	7-7.99	91	227	63.05
7	8-8.99	74	136	37.78
8	9-9.99	36	62	17.22
9	10-10.99	12	26	7.22
10	11-11.99	10	14	3.88
11	12-12.99	2	4	1.11
12	13-13.99	2	2	0.55

3.2. Otamiri Flow Duration Curve

The lower value of each class interval as (y-axis,), was then plotted against the percentage of time exceeded by flow as (x-axis) to obtain the flow duration curve FDC and is shown in Figure 2. FDC is also plotted on a log-log paper to provide a qualitative description of runoff variability in the stream (Figure 3). The median-flows (Q_{50}) which is equal to flow that occurred 50% of time, was obtained by dividing the FDC into two equal parts at the central portion of the graph. The median-flows help to identify the base-flow contribution of the river. The median flow was obtained from Figure 2 as 7.5 m^3/s. Thus, the part of the curve which is below the median (Q_{50}%) represented low-flow condition. As it is shown on the flow duration curve for Otamiri River plotted in Figure 2, the two extreme ends have steep slope bending upward in the case of upper-flow region and bending downward in case of lower-flow. Flow values corresponding to different percentage exceedence were recorded in Table 4. The availability of each flow value was determined by selecting the percentage exceedence for that flow as shown in Table 4. The power potentials are equally recorded in Table 4. The flow that gives the maximum energy generation which is the design flow, Q_d was estimated as 9.22 m^3/s.

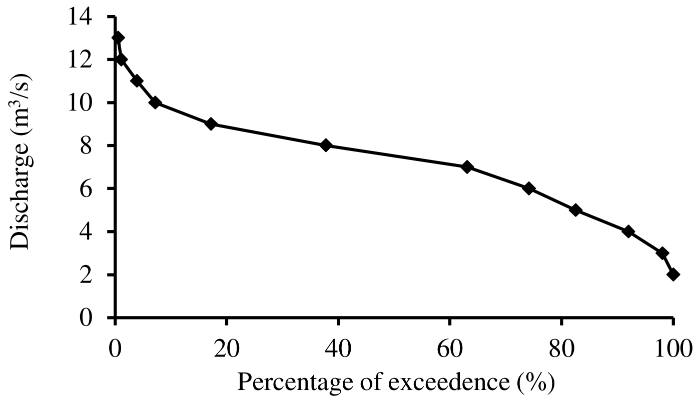

Figure 2: Flow duration curve of Otamiri River

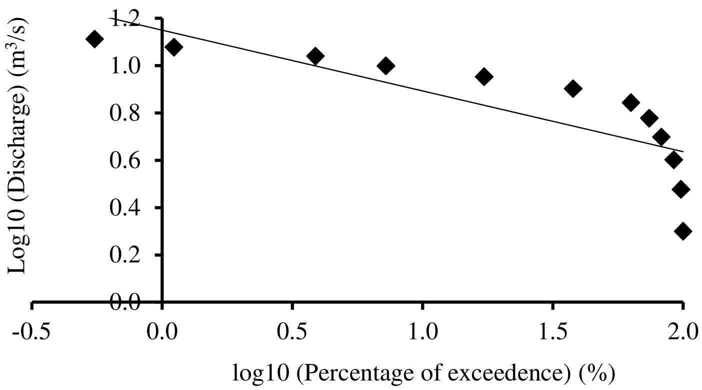

Figure 3: Flow duration curve of Otamiri River on Log-Log Scale

Table 4: Determination of design flows

Design flows	Q_{10}	Q_{20}	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}
Discharge (m^3/s)	9.22	9.00	8.86	7.92	7.52	7.12	6.37	5.30	4.21
Availability (months)	1.30	2.40	3.60	4.80	6.00	7.20	8.40	9.60	10.80
Gross head (m)	3.20	3.20	3.20	3.30	3.30	3.30	3.30	3.30	3.30
Power potential (kW)	206.53	201.60	198.46	177.41	168.45	159.49	142.69	118.72	94.30
Annual energy generation (kWh)	267,660.29	348,364.80	514,418.69	613,122.05	727,695.36	826,785.79	862,977.02	820,592.64	733,307.90

3.3. Estimated Power Potential of Otamiri River

This maximum flow (Q_{15}) was determined by reading off the flow corresponding to Q_{15} from the flow duration curve i.e., Q_{15} = 9.22 m^3/s**.** The average flow, Q_{av}, was computed from the mean monthly discharge data by dividing the total annual discharge by the total number of years of data, Q_{av} = 7.21 m^3/s. The minimum dependable flow, Q_{90}, was obtained from the FDC (Figure 2) as 7.21 m^3/s. The power potential, P was computed as 175.38 kW. The installed capacity, P_{IC}, for this river at the site was estimated as 224. 28 kW. The firm or dependable power P_F, was estimated as 102.41 kW. The average annual energy generated, E, from a power plant was computed as 1,536, 357.27 kWh.

4. CONCLUSION

Flow duration curve and minimum flows for Otamiri at Nkede gauging station were successfully analyzed. Various flow values corresponding to different percentage exceedence Q_{15}, Q_{20}, Q_{30}, Q_{50}, Q_{60}, Q_{70}, Q_{80} and Q_{90} were read off the FDC. This maximum flow and average flow were determined as 9.22 m^3/s and 7.21

m^3/s respectively while. The power potential and installed capacity were computed as 175.38 kW and 224. 28 kW respectively. The dependable power and average annual energy generated were estimated as 102.41 kW and 1,536, 357.27 kWh respectively. From the estimated flow duration curve for Otamiri River, the monthly flow which is equaled or exceeded 90% of time Q_{90} is 7.2 m^3/s. This flow which is known as the lowest flow for Otamiri River can be considered in assessing the reliability of Otamiri River for hydropower generation as well as environmental flow requirement in the river catchment.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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