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PREDICTION OF RE-AERATION COEFFICIENT OF RIVERS FROM STREAM FLOW CHARACTERISTIC

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Abstract

Stream re-aeration is the physical absorption of atmospheric oxygen by flowing in water, and this is primarily how the stream replenishes the depleted oxygen that is consumed in the decomposition of organic matter. One important parameter is the re-aeration rate, which allows for the evaluation of the quality and self-purification rate of water bodies. The re-aeration rate can be determined using a variety of methods, such as empirical and semi-empirical equations that can rapidly produce estimates based on hydraulic and hydrodynamic variables. However, depending on the variables, these equations often produce very different results and can lead to underestimated or overestimated values. In this study, a new re-aeration model was developed, designated as the N-Model, and its results were compared with some selected existing models to evaluate its suitability for use without vigorous laboratory work. The selected models include O'Connor, Parkhurst, Churchill, Krenkel, Thackston, and Owen. The re-aeration coefficient was computed using data collected from four selected rivers, namely: Otammiri, Kaduna, Adada,and Oshika Lake. The re-aeration coefficient for the Otammiri River was 0.075; O'Connor's model provided a very accurate result of 0.0753, with a correlation coefficient of 99.2%. N-Model predicted 0.076, giving an accuracy of 98.4%, and Parkhurst gave 0.078, unlike the others, Churchill, Krenkel, Thackston, and Owen, with percentage error values of 99.95%, 92.6%, 89.3%, and 73.17%, respectively. In summary, N-Model produced an average 98.9% correlation coefficient with less than 4% standard error, while O'Connor gave 84.6% for all three rivers except Oshika Lake, Parkhurst gave 46.8%, and others produced a significantly low correlation of between 13.222.4%. The standard error values for the re-aeration models ranged from 4% to 2208.35%. The order of performance of the various re-aeration models used was based on their proximity based on the value to past laboratory work done on the rivers.

Keywords: Re-Aeration Coefficient, Oxygen, Rivers, Re-Aeration Models, Stream Flow.

Introduction

Water is a necessary component of life on earth, making up about two-thirds of the human body. Cole and Wells (2002) presented a model aimed at estimating the rate of reaeration in streams, which is crucial for water quality modeling. Reaeration refers to the process by which oxygen from the atmosphere is transferred into water, which is essential for maintaining adequate levels of dissolved oxygen for aquatic life. The model proposed by Cole and Wells considers various factors influencing reaeration, such as stream flow characteristics. A human being can survive for up to a month without food, according to a report by Guo, L., and Diamond, J. (2004). but they can only do so for one week without water. Schneider and Schindler (2006) conducted research focusing on predicting river reaeration coefficients based on flow velocity and depth. Reaeration coefficients are crucial for understanding the oxygen transfer dynamics in rivers, which directly affects water quality and aquatic life. The study likely involved field measurements of flow velocity and depth in various river locations, along with simultaneous measurements of dissolved oxygen concentrations.

Fresh water is a valuable and limited resource that is essential for sustainable development, economic expansion, social stability, and the reduction of poverty. Due to the fact that millions of women and children spend several hours a day collecting water, there is a correlation between water shortage and poverty, significant economic waste (caused by the expense of health care), productivity losses, and labor diversion. McCutcheon and O'Connor (2007) likely conducted research focused on predicting river reaeration coefficients using hydraulic geometry principles. Reaeration coefficients play a critical role in understanding oxygen transfer dynamics in rivers, which directly impact water quality and aquatic ecosystems. Hydraulic geometry involves studying how river channel characteristics, such as width, depth, and slope, influence flow dynamics. Their research is likely valuable for water resource management and environmental protection, as it provides insights into the factors influencing oxygen dynamics in rivers. Accurate prediction of reaeration coefficients can inform strategies for maintaining healthy aquatic ecosystems and addressing water quality challenges. Overall, McCutcheon and O'Connor's study likely advances our understanding of reaeration processes in rivers and their implications for environmental management. Having access to clean, safe drinking water is crucial for maintaining public health. This is due to the fact that adequate sanitation and hygiene practices, such as hand washing, bathing, flushing toilets, washing clothes, and cleaning the house, require clean water in the proper quantity, and that a lack of such practices exposes people to a range of health-related issues, such as diseases that are water-borne or related, such as diarrhea, amoebiasis, typhoid, and cholera. 1.8 million children die worldwide each year as a result of diarrhea, and 443 million school days are lost each year from water-related illnesses.

Webster et al. (2008). There is a propensity for the physical, biological, and chemical characteristics of the water to change when stratification of a river develops owing to variation in density between two layers, which may come from either salinity or temperature differential or a mix of both. The mixed depths that are exposed to surface aeration are constrained by stratification. Re-aeration is also restricted to the surface when a body of water is stratified and a warmer layer is isolated near the surface layer. When winds are blowing harder and when it gets cooler at night, the surface mixed depth rises. A larger quantity of oxygen is transported to the water body during times of increased wind because this greater mixed depth permits a larger portion of the water volume to be exposed to re-aeration (Bowman et al., 2010). The epilimnion, metalimnion, and hypolimnion are the three separate portions of the river that were created as a result of stratification. Due to a variety of reasons, these adjustments are frequently inappropriate. As the nutrients are absorbed by photosynthetic plants, the oxygen content of the epilimnion decreases. The hypolimnion separates from the other parts and is frequently referred to as stagnant. The epilimnion's organic waste is transported to the hypolimnion as debris. Arheimer and Lindström (2011). The amount of dissolved oxygen in the water decreases as bacterial breakdown of the organic material gets going. Municipalities will need to spend more money on further treatment to improve the water's quality and get more use out of the water taken from the hypolimnion. The main reason for aquatic life mortality, decreased water quality, and serious health risks to humans is the presence of organic chemicals in surface water, such as rivers, as a result of various anthropogenic activities. The river's discharge and, consequently, the amount of contaminants in the water are significantly influenced by the concept of runoff. Feng and Guo (2021). In comparison to organic chemicals, inorganic chemicals make up a larger portion of water. Inorganic minerals typically include significant amounts of heavy metals. In the human body, heavy metals like lead (Pb) build up and interfere with how the nervous system works. In addition, traces of metals, including chromium (Cr) and cadmium (Cd), are linked to cancer, cardiovascular disease, kidney-related illnesses, and neurocognitive disorders. Municipal and industrial wastes have been dumped into rivers since 1963. However, because rivers have the ability to purify themselves, the presence of municipal and industrial waste in a stream does not necessarily indicate that the stream is contaminated. Nataraj and Ramesh (2013).

The amount of dissolved oxygen in water is a crucial element since it affects everything from the water's quality to the survival of plants and animals. The total amount of oxygen that is currently present in the water is referred to as dissolved oxygen. Aquatic plants and the atmosphere are two different sources of oxygen for bodies of water. Aquatic plants use the process of photosynthesis to produce dissolved oxygen. Keep in mind that, compared to the still water found in a lake or pond, rushing water will always dissolve more oxygen. Biedenharn and Colarullo (2018).

METHODOLOGY

The re-aeration coefficient of rivers is a crucial parameter in understanding the exchange of gases, such as oxygen and carbon dioxide, between the water and the atmosphere. It directly influences water quality and ecosystem health. Predicting this coefficient involves assessing

various stream flow characteristics, which are indicators of how water moves through the river system.

Experimental Data of Re-aeration Coefficient of Some Selected Rivers Obtained from Literature

The mean values of data from Otammiri, Adada, Kaduna River and Oshika Lake was determined and the result tabulated in Table 1 below.

Table 1: Mean stream flow data of selected rivers obtained from literature (see various sources of the raw data in the appendices)

PARAMETERS	OTAMMIRI	OSHIKA LAKE	RIVER KADUNA	A D A D A
Mean depth (h)(m)	3.501	2.3	1.33	0.758
Av. velocity (u)(m/s)	0.016	0.00105	0.1975	0.4084
Surface elevation	0.00005	2.971×10^{-10}	0.000306	0.0000202
Temperature (°C)	20	28	23	28.2

Model Development from Stream flow Characteristics

The mean stream flow data from three rivers, namely; Otammiri, Adada and River Kaduna were used to calibrate the empirical model developed based on O'connor and Dobbins (1956) equation. The model was formulated thus;

$$K_2 = \frac{xU^y}{D^z} \quad 3.1$$

Where;

K_2 Is the re-aeration coefficient, x, y and z are constants, U is the river velocity in m/s and D is the river depth in meters (m).

The model was calibrated as follows;

$\ln K_2 = \ln x + y\ln U - z\ln D$ 3.2

$-2.590 = \ln x - 4.135y - 1.253z$ 3.2a

$-0.164 = \ln x - 1.622y - 0.285z$ 3.2b

$-0.162 = \ln x - 0.895y + 0.277z$ 3.2c

Solving equations (3.2a), (3.2b) and (3.2c) simultaneously, yield the values of the constants; x = 9.44, y = 1.921 and z = -2.482, substituting these values in equation (3.1) yields;

$$K_2 = 9.44\frac{U^{1.921}}{D^{-2.482}} \quad 3.3$$

Equation (3.3) is our newly formulated model and will be designated thus as N-Model in this study.

Hydrodynamic Models

Mathematical models are used to simulate the flow of water in rivers. These models take into account the stream flow characteristics mentioned above to predict how gases are transported and exchanged within the water body.

So many researchers have worked on and developed various concepts and formulas for the determination of re-aeration constant. The re-aeration constant k_2 by means of tracer study is determined using O'connor's equation stated as:

$$k_2 = \frac{3.9V^{0.5}\sqrt{(1.037)^{(T-20)}}}{H^{3/2}} \quad 3.4$$

Where V is the mean stream velocity in m/s, T is the temperature in ℃ and H is the average depth of river in m.

Sivapalan, M., & Blöschl, G. (2020).

$$K_2 = 0.03453\frac{V^{2.695}}{D^{3.085}SL^{0.823}}; \quad 3.5$$

Krenkel and Orlob (1963),

$$K_2 = 234.5\frac{(V\,SL)^{0.404}}{D^{0.66}}; \quad 3.6$$

Owens and others (1964),

$$K_2 = 23.23\frac{V^{0.73}}{D^{1.75}}; \quad 3.7$$

Dobbins (1965),

$$K_2 = 116.6\frac{1+F^2}{(0.9+F)^{1.5}}\frac{(V\,SL)^{0.375}}{D}\coth[\frac{4.10(V\,SL)^{0.125}}{(0.9+F)^{0.5}}; \quad 3.8$$

Where;

Coth is the hyperbolic cotangent of the angle in radians,

F is the Froude number, which is a dimensionless ratio defined by

$$F = \frac{V}{(g\,D)^{0.5}}, \quad 3.9$$

Where g is the acceleration due to gravity in feet per second squared

Parkhurst and Pomeroy (1972),

$$K_2 = 48.39\frac{(1+0.17F^2)(V\,SL)^{0.375}}{D}; \quad 3.10$$

Thackston and Krenkel (1969),

$$K_2 = 24.94\frac{(1+(F)^{0.5})u^*}{D}; \quad 3.11$$

Where F is the Froude number,

u^* is the average wind shear velocity measured in feet per second defined as

$$u^* = (g\,D\,SL)^{0.5}; \quad 3.11a$$

Where V remains mean stream velocity in m/s

SL is the water surface slope (obtained from topographic map of the study area)

D is the average depth of river, T is temperature (at 20℃), g is the acceleration due to gravity in m/s^2 (9.81m/s^2)

In 2013, Omole D. O and others presented a shortlist of ten re-aeration constant models for evaluation using various data sets obtained from the Atuwara River in Ota, Ogun State. This records obtained from literature will further be used to validate the New Model derived in this study.

RESULTS AND DISCUSSION

From the values of the re-aeration coefficients obtained, it is observed that the re-aeration coefficient increases with increasing velocity, implying an increased rate of oxygen transfer from the atmosphere to the water. An inverse proportionality relationship exists between the re-aeration coefficient and the water depth. The re-aeration coefficient decreases as the water depth increases, and the volumetric amount of oxygen produced by phytoplankton becomes smaller. This can be attributed to the fact that the water depth affects the intensity of solar radiation. Hence, as the water depth increases, the intensity of sunlight penetrating the river that the phytoplankton uses is greatly reduced. As a result of the effect of depth on the re-aeration coefficient and the amount of oxygen required for photosynthesis by the phytoplankton, we would expect that the DO sag curve should drop lower with increasing depth due to the time it will take for oxygen at the top to diffuse to the bottom of the river.

Computation of re-aeration coefficients and comparison with other existing relationships:

Table 2: Results of re-aeration coefficients computed with different re-aeration models

River	O'connor	Churchill and others	Krenkel and Orlob	Owens and others	New Model	Parkhurst and pomeroy	Thackston and Krenkel	Measured Value
Otammiri	0.0753	3.62E-05	0.354	0.127	0.076	0.078	0.311	0.075
Kaduna	1.078	0.141	3.841	4.32	0.848	0.954	1.465	0.8481
Adada	4.383	7.946	6.316	19.621	0.845	1.888	3.971	0.85
Oshika lake	0.042	0.00172	0.0012	0.0362	0.0041	0.00043	0.000901	0.069

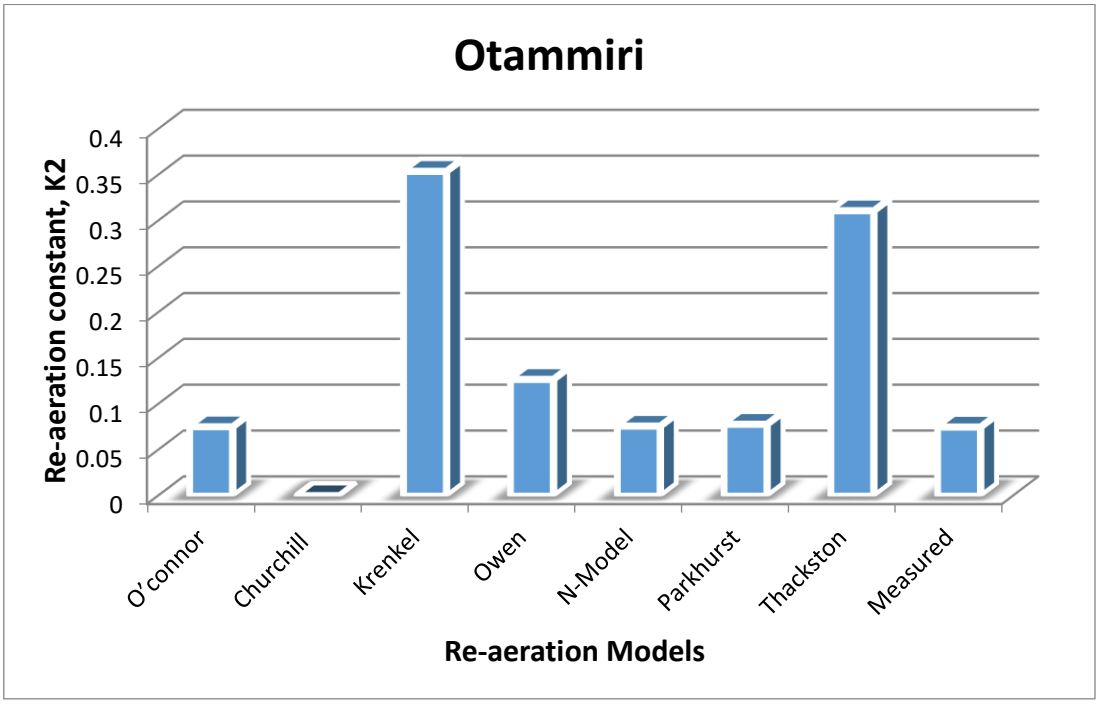


Figure 1: Variation of K_2 with Re-aeration models for Otammiri River

The order of performance of the various re-aeration models used was based on their proximity in value to past laboratory work done on the rivers. The re-aeration coefficient for the Otammiri River was 0.075, as shown in figure 1 above; O'Connor's model provided a very accurate result of 0.0753, with a correlation coefficient of 99.2%. N-Model predicted 0.076, giving an accuracy of 98.4%, and Parkhurst gave 0.078, unlike the others, Churchill, Krenkel, Thackston, and Owen, with percentage error values of 99.95%, 92.6%, 89.3%, and 73.17%, respectively. The reason for the difference could be attributed to the difference in stream conditions under which each was derived. Such stream conditions could include the nature of the stream, location, type of effluent discharged, and geometric properties of the stream.

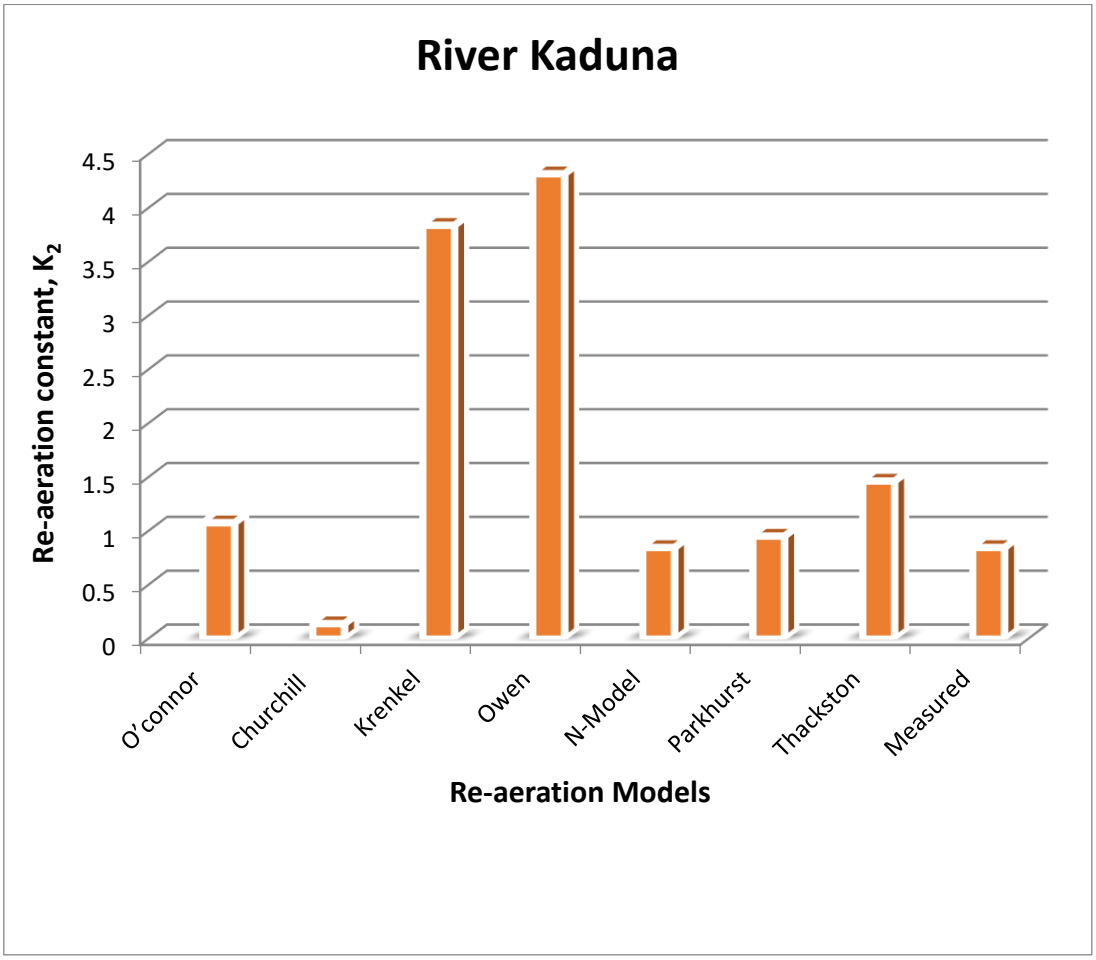


Figure 2: Variation of K_2 with Re-aeration models for River Kaduna

The re-aeration coefficient for River Kaduna was 0.8481. The N-Model predicted an accurate value of 0.848 (see figure 2), producing a 99.8% correlation coefficient, while the Parkhurst model gave a result of 0.954, which we can conclude was in near agreement with the reported re-aeration coefficient with a 74.6% correlation coefficient, unlike the others, Owen, Krenkel, Churchill, Thackston, and O'Connor, with standard error values of 409.37%, 352.89%, 83.37%, 72.74%, and 27.11%, respectively.

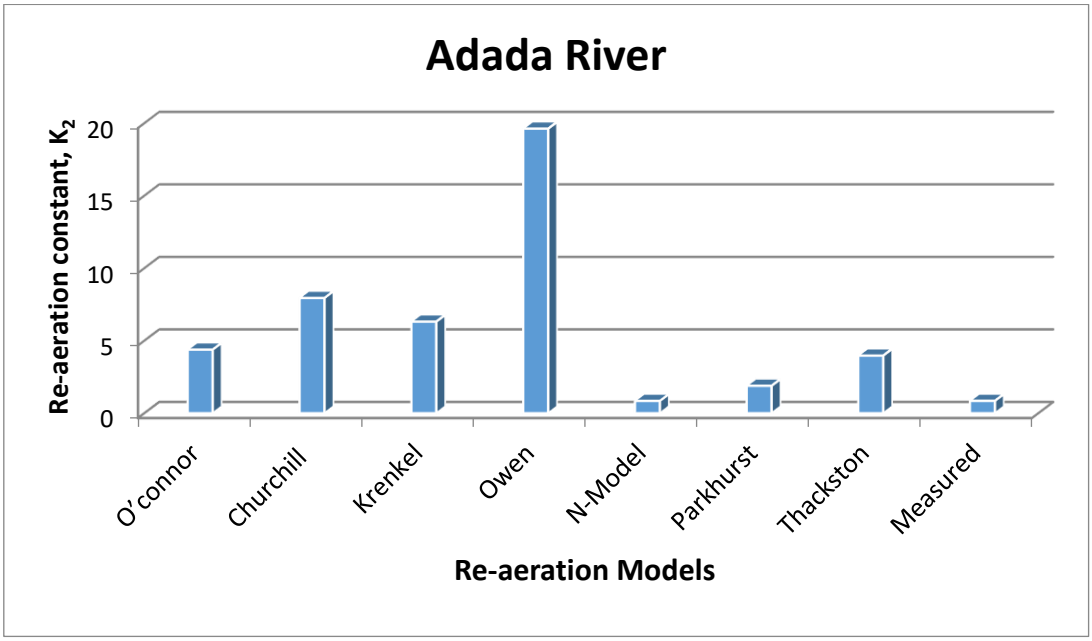


Figure 3: Variation of K_2 with Re-aeration models for Adada River

The re-aeration coefficient for Adada River gave had a mean value of 0.85 as measured; see figure 3 above. The N-Model predicted a value of 0.845 with an accuracy of 99.8% correlation coefficient, while Parkhurst produced a value of 1.888, which is in closest agreement with the stated result with a 52.7% correlation, unlike the other re-aeration models, Owen, Churchill, Krenkel, O'connor, and Thackston, with standard errors of 2208.35%, 834.82%, 643.05%, 415.64%, and 367.18%, respectively.

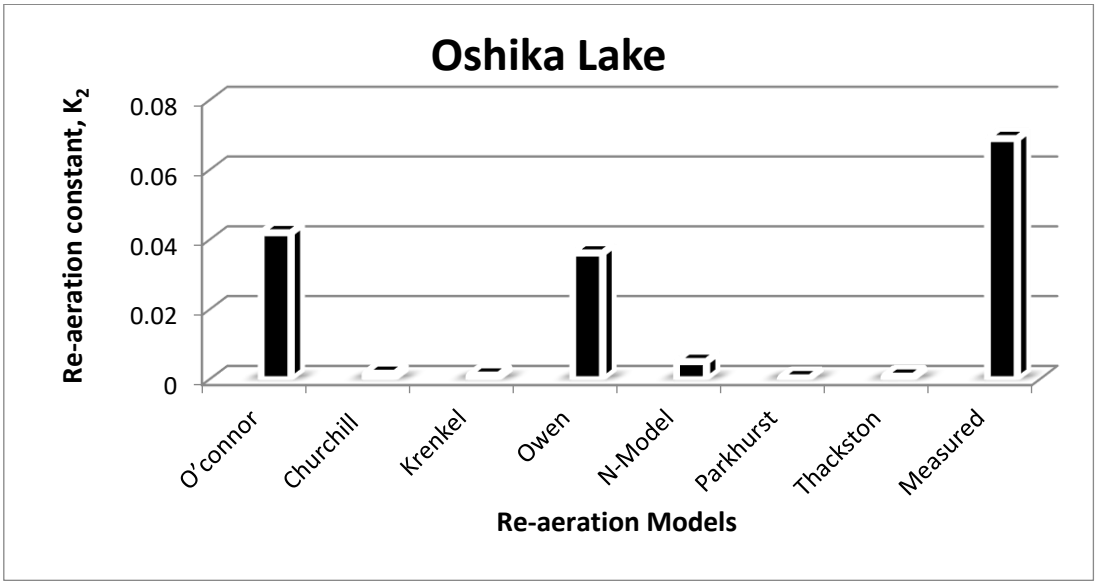


Figure 4: Variation of K_2 with Re-aeration models for Oshika Lake

The coefficient of re-aeration for Oshika Lake was reported as 0.069. O'Connor's model provided a re-aeration coefficient of 0.042, as shown in figure 4, amounting to a 57.8% correlation value, and Owen gave 0.0362, producing a 51.4% correlation, which we can consider to be a little reasonable unlike the others: Thackston, Parkhurst, Churchill, Krenkel, and the N-Model, with standard error values of 99.79%, 99.38%, 95.69%, 95.26%, and 87.54%, respectively. Both re-aeration models produced by O'Connor and N-Model have proved to be the most reliable among the others; little wonder, N-Model was empirically derived from O'Connor and Dobbins equations. However, the accuracy of these models cannot be guaranteed when used to theoretically predict the re-aeration coefficient of rivers without having to go through some phase of laboratory testing. Notwithstanding, these models could offer some reasonable ideas about the re-aeration rate of rivers.

Conclusions

The order of performance of the various re-aeration models used was based on their proximity in value to past laboratory work done on the rivers. The re-aeration coefficient of the Otammiri River varied from 0.0000362 to 0.141 for the Kaduna River, 1.888 for the Adada River, and 0.0001440.042 for Oshika Lake. O'Connor and N-Model re-aeration models could be conveniently adopted. The re-aeration coefficient is directly proportional to stream velocity and inversely proportional to water depth. The values for the re-aeration coefficients obtained are significantly low, implying that these rivers are polluted to a great degree and, as such, are unsafe as potable water without treatment for human consumption. The standard error values for the re-aeration models ranged from 4% to 2208.35%. The reason for this enormous error in calculating with these models was due to the fact that the prevailing stream conditions from which these models were formulated vary significantly from the rivers being considered here. This fact comes to bear with the result obtained from Oshika Lake when the N-Model was used. For the three other rivers, viz., Otammiri, Kaduna, and Adada, an average coefficient of correlation of 98.9% accuracy was reported with a standard error of less than 4% estimation, whereas an estimated error of 87.54% was recorded when applied to Oshika Lake. This is because the calibration of the N-Model was done using the stream flow characteristics of these rivers, hence the high level of accuracy. The self-purification capacity of these rivers is low.

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