PREDICTION OF RE-AERATION COEFFICIENT OF RIVERS FROM STREAMFLOW CHARACTERISTICS

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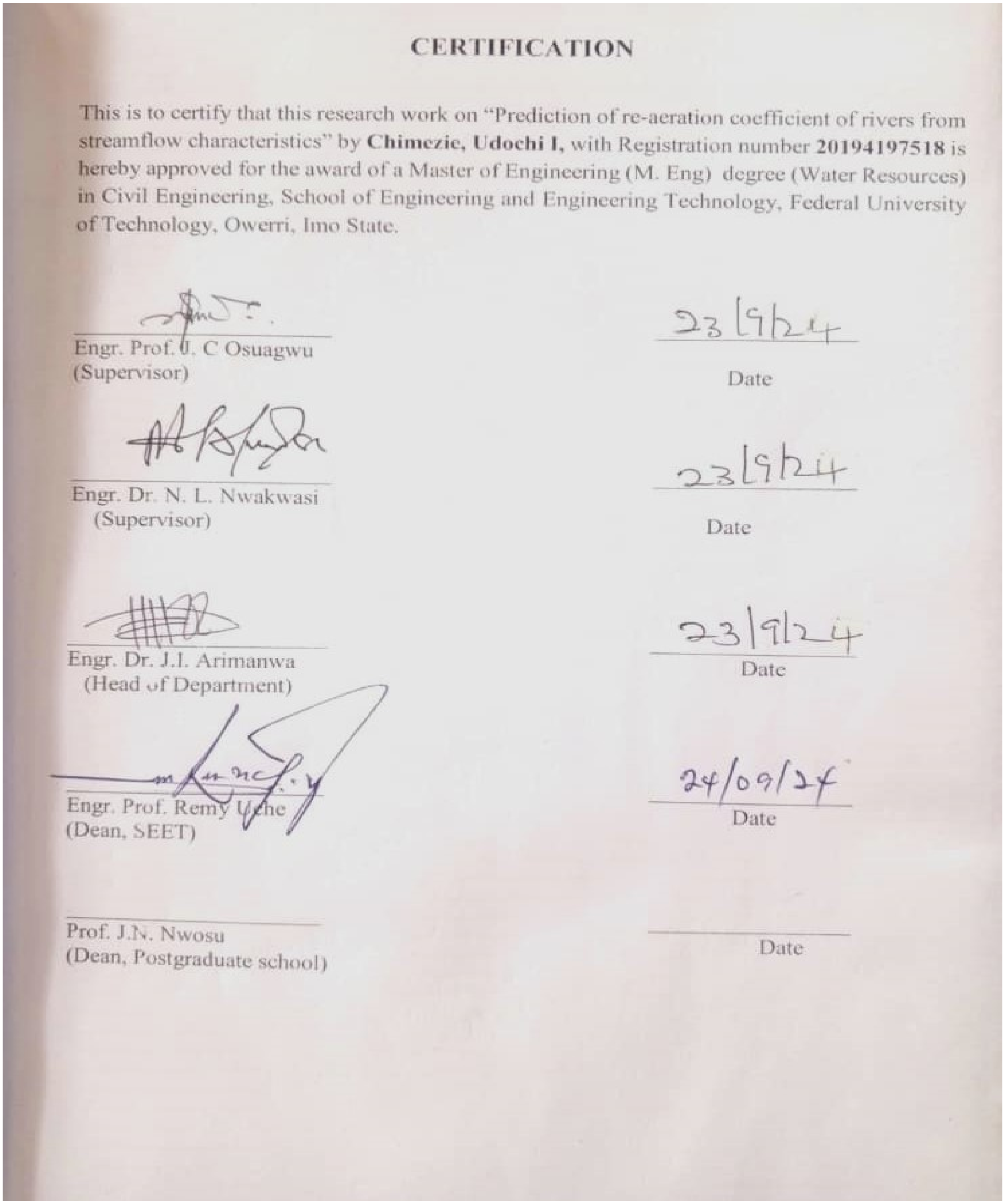

CERTIFICATION

This is to certify that this research work on "Prediction of re-aeration coefficient of rivers from streamflow characteristics" by **Chimezie, Udochi I,** with Registration number **20194197518** is hereby approved for the award of a Master of Engineering (M. Eng) degree (Water Resources) in Civil Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Owerri, Imo State.

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DEDICATION

This work is dedicated to God Almighty for the strength to bring this work to completion.

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ABSTRACT

In this study, a new model, designated as the N-Model, was developed to predict the re-aeration coefficient of rivers using streamflow characteristics. Re-aeration is an important phenomenon that sustains dissolved oxygen levels in receiving waters to support aquatic life and natural self-purification of streams and rivers. Development of the N-Model was done for the sole purpose of getting a more accurate model that could easily be applied with no heavy laboratory work in order to be put into application on site. The performance of the N-Model is compared against various existing empirical models like O'Connor, Parkhurst, Churchill, Krenkel, Thackston, and Owen. Data collection was done from the following rivers: Otammiri, Kaduna, Adada, Oshika lake and Atuwara. Using O'Connor's model, the re-aeration coefficient of the Otammiri River was found to be 0.0753 with a very high correlation coefficient of 99.2%. The N-Model predicted the value for Otammiri River to be 0.076 with an accuracy of 98.4%. This was determined by comparing the predicted value of the N-Model with observed data, where the minimal difference between the two (0.076 vs. 0.075) indicated that the model was highly effective in estimating the re-aeration coefficient. The model by Parkhurst produced a coefficient of 0.078 while other models like the ones by Churchill and Owen showed much higher discrepancies with percentage errors of over 70%. Across all rivers, the N-Model demonstrated strong predictive accuracy, with an overall correlation coefficient of 98.9% and a low standard error of less than 4%. However, other models like Churchill and Krenkel give very small correlation coefficients often less than 25%, indicating that the N-Model offers a reliable and efficient alternative for estimating re-aeration coefficients from streamflow characteristics in varying environments.

Keywords: Re-aeration coefficient, rivers, models stream flow data, performance.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Water plays a significant role in maintaining human health and welfare. In recent times, clean drinking water is recognized as a fundamental human right. River waters are most times the recipient of treated and sometimes untreated wastewater. One of the global environmental issues is surface water pollution. Flowing surface water bodies have the natural capacity to purify themselves from pollutions that come into them from external sources (Garg, 2006; Longe and Omole, 2008).

In all processes of stream purification which requires that there is an adequate reserve of dissolved oxygen, two major factors should be considered in limiting the degree of pollution. The first factor is the biochemical de-oxygenation rate of the river water and the other is the rate and degree of oxygen replenishment which could result from three natural processes. These includes; Dilution water flowing from tributaries and distributaries into the stream, biological re-oxygenation through the activities of photosynthetic plants and atmospheric Re-aeration. Of the above mentioned processes, atmospheric re-aeration is the most important and cannot be overlooked. Stream re-aeration is the physical absorption of atmospheric oxygen by flowing waters. This is primarily how the stream replenishes depleted oxygen consumed in the decomposition of organic matter.

When stratification of a river occurs due to difference in density between two layers which may arise from either salinity or temperature differential or a combination of both, there is tendency for the physical, biological and chemical properties of the water to change. Stratification limits the mixed depths that are exposed to surface aeration. When a water body is stratified, with a warmer layer isolated near the surface layer, re-aeration is also limited to the surface. The surface mixed depth increases when wind speeds are higher and at night from cooling. This greater mixed depth allows a larger fraction of the water volume to be exposed to re-aeration, so a greater mass of oxygen is transferred to the water body during periods of higher wind speed (Jones and Stokes 2003). The stratification process separated the river into three distinct sections namely the epilimnion, the metalimnion and the hypolimnion. These changes are most times unsuitable due to many factors. The epilimnion becomes depleted of oxygen as photosynthetic plants absorb the nutrients. The hypolimnion becomes isolated from the other sections and is often described as being stagnant. The hypolimnion is the receptor of debris of organic matter from the epilimnion. As bacterial decomposition of the organic debris begins, there is a depletion of the available dissolved oxygen in water. Water drawn from the hypolimnion for usage by municipalities will require additional treatment to remove pathogens and improve the quality of water incurring higher costs.

Organic compounds introduced into surface water, such as rivers, through various human activities are a leading cause of aquatic life mortality, declining water quality, and pose significant risks to human health. The principle of runoff which refers to the process by which water from precipitation, snowmelt, or irrigation flows over the land surface and into nearby water bodies has a large influence on the discharge of the river and in turn, the level of contaminants in the water. In water bodies, there are a higher percentage of inorganic chemicals in comparison to organic chemicals. Heavy metals tend to form a large part of the inorganic minerals. Heavy metals such as Lead (Pb) accumulate in the human system and disrupt the functions of the nervous system. In addition, cancer, cardiovascular diseases, kidney related diseases and neurocognitive diseases are attributed to the traces of metals such as Chromium (Cr) and Cadmium (Cd).

Natural re-aeration is an excellent process by which the river replenishes depleted oxygen consumed in the oxidation of organic matter contained in the water. If the dissolved oxygen in water drops below generally acceptable values, the aquatic life existing in the water is at very high risk of death which in turn affects the quality of water which makes it unsuitable for use and unpalatable. Dissolved oxygen is considered as a key water quality parameter. Re-aeration is the most natural means by which the river can reclaim the concentration of dissolved oxygen and as such, it is important to determine the re-aeration rate.

Furthermore, oxygen which is a product of photosynthesis dissolves by diffusion from the atmosphere. The concentration of oxygen saturation varies with the temperature of water. A three-fourth of the total earth's oxygen supply comes from the process of photosynthesis in the ocean. When these plants die, they are consumed by the bacteria in the food chain which then reproduces, using larger amounts of oxygen, leading to reduced oxygen levels. The amount of dissolved oxygen required by an aquatic life is dependent on its species, size, the water temperature, time of feeding, degree of physical activity present, pollutants among others. For example, crabs, worms and oysters need 1-6mg/L and shallow fish require 4-15mg/L. Trout consumes about 50-60 milligram (mg) of oxygen per hour at 41degree Fahrenheit and may need five times the amount at 77 degrees Fahrenheit. The temperature of water also controls the consumption of oxygen as there is twice an increase in rate with a 10 degrees Celsius increase in temperature with the temperature tolerance spectrum of the species. Healthy water should have concentrations of dissolved oxygen above 6.5-8 mg/L and between about 80-120% which is above the chronic criterion for growth.

Early studies recognized the relevance of dissolved oxygen balance as one of the most easily determined quantities that indicate and also controls the self purification of rivers and streams. A high concentration of dissolved oxygen in a water source used to supply a community is good as it imparts better taste to drinking water. High dissolved oxygen levels may also have adverse effects such as the corrosion of water pipes used in the distribution system. The dynamics of the dissolved oxygen in water can be affected by respiration, mineralization, nitrification and sediment water exchange. Biologically speaking, knowledge of the dissolved oxygen in water provides a better measure for assessment of the quality of water than fecal coliform.

1.2 Statement of problem

The dissolved oxygen (DO) content of surface water bodies is one of the important indicators of its quality. Since the pioneering work of Streeter and Phelps (Streeter and Phelps, 1925) scientists have attempted to predict DO of surface water as accurately as possible by modeling re-aeration coefficients (k_2) for different environments and conditions which has resulted in hundreds of existing k_2 models, (Bennett and Rathbun, 1972; Bowie; 1985). The development of a typical k_2 requires repeated field trips for water sampling, stream geometry measurements, laboratory tests of water samples, and data analysis (Agunwamba 2007). This could be costly in terms of expended energy, time, and financial resources.

1.3 Objectives of Study

The main objective of this research is to predict the re-aeration coefficient of rivers from streamflow characteristics.

The specific objectives are:

i. To gather experimental data on the re-aeration coefficients of selected rivers from existing literature.
ii. To establish an empirical model that predicts the re-aeration coefficient (K_2) of rivers based on their streamflow characteristics.
iii. To calculate the re-aeration coefficient (K_2) for various rivers using the developed empirical relationship.
iv. To evaluate and compare the calculated re-aeration coefficients against those derived from established models in the literature.

1.4 Scope of Study

The scope of this study is restricted to investigation, data collection and formulation of a new empirical model for the determination of the re-aeration coefficient from four rivers, Otammiri in Imo State, Adada that flows through Enugu State, Kaduna River flowing through Kaduna State and Oshika Lake in Rivers State. The effect of photosynthesis, respiration by aquatic life, runoff, climate and biodegradation of organic matter will be ignored in determining the re-aeration rate.

1.5 Significance of Study

The significance of this study lies in its ability to enhance water quality management by offering a more accurate and practical approach for predicting the re-aeration coefficient (k_2) of rivers. This coefficient plays a critical role in determining a river's capacity to replenish dissolved oxygen, which is essential for maintaining healthy aquatic ecosystems and supporting life. By developing the N-Model, the study provides a valuable tool that eliminates the need for extensive laboratory work, making it both cost-effective and accessible for water resource management. Additionally, the findings contribute to better-informed environmental policies and improved understanding of river dynamics, especially in regions where data on re-aeration rates are scarce. This will add to mitigating the effects of pollution on aquatic ecosystems in terms of protection for marine organisms and reducing possible health risks for the population making use of such waters.

CHAPTER TWO

LITERATURE REVIEW

2.1 Basic Terms of Importance in the Study of Re-Aeration

The process of reaeration involves the introduction of air into water, oxygen from the air dissolves into the water and replenishes the dissolved oxygen. The following terms explained below are of importance in the study of Reaeration.

2.1.1 Aeration

This is a unit process which involves increasing the oxygen saturation of water by the introduction of oxygen into it. It is a very lengthy process but has proven effective overtime in the biological treatment of waste water. There are various methods by which water can be aerated namely surface and sub-surface aeration. Aeration can be achieved by diffusing air into water or waste water. Sufficient turbulence aids the increase of aeration of flowing water. The resulting contact that occurs between the waste water and the air can be accomplished by the use of mechanical systems (surface aeration) or by use of compressed air systems (bubble aeration). Small bodies of water rely on the process of aeration to maintain sufficient oxygenation in water to support aquatic life.

The rate of oxygen transfer from air into wastewater is given by the equation;

$$\frac{dC}{dt} = Ka\,(Cs - C) \qquad 2.1$$

Where;

Ka is the re-aeration coefficient, Cs is the saturation concentration of oxygen and C is the oxygen concentration in waste water

2.1.2 Biochemical Oxygen Demand

This is the sum of nitrogenous and carbonaceous demand. This is the amount of dissolved oxygen used by micro organisms for the biochemical degradation of organic matter and the oxidation of inorganic matter such as ferrous iron and sulphides during a specified incubation period, usually five days. Samples must often be diluted prior to incubation (Arora & Keshari, 2018). The amount of organic matter determines the amount of BOD present. The higher the organic matter content, the higher the BOD; and the higher the BOD, the lower the amount of dissolved oxygen made available to aquatic life. The BOD can be used reliably to gauge the rate of pollution of a water body. A high BOD signifies the presence of a large amount of organic pollution (Rao & Kumar, 2017). BOD interacts with residence time and in self-purification modeling, the amount of oxygen consumed by bacteria for the aerobic oxidation of organic matter in water is given as;

$$\frac{dL}{dt} = -K1 \qquad 2.2$$

Where;

L is the carbonaceous BOD varying with time t, and

K1 is the de-oxygenation coefficient depending basically on the nature and concentration of substratum, the quantity of bacteria and water temperature in rivers. (Dobbins, 1964).

The natural re-aeration process tends to make up for the existing oxygen deficit whose variation can be expressed as;

$$\frac{dD}{dt} = -K2D \qquad 2.3$$

Where;

K2 is the re-aeration coefficient dependent on water temperature, stream velocity, water depth and a few other factors. The oxygen deficit which represents the difference between the existing dissolved oxygen and the saturated dissolved oxygen is given as;

$$D = Dos - DO \qquad 2.4$$

Streeter and Phelps (1925) stated that, the rate at which the dissolved oxygen deficit varies with time, as a composite effect of both de-oxygenation and superficial re-aeration is written as;

$$\frac{dD}{dt} = K1L - K2D \qquad 2.5$$

Integrating equation 2.5 by beginning from BOD upstream and deficit. L0 and D0, we have;

$$D = \frac{K1}{K2 - K1} L0\left(e^{-K_1 t} - e^{-K_2 t}\right) + D_0 e^{-K_2 t} \qquad 2.6$$

2.1.3 Dissolved Oxygen

This is a measure of the quantity of oxygen dissolved in water. The presence of dissolved oxygen is important for the survival of aquatic life. The mean requisite for dissolved oxygen by Ostracodes falls within a very narrow margin of 7.3-9.5mg/L. The solubility of oxygen in water decreases with increased salinity and temperature and altitude. As temperature increases, so does the demand for oxygen due to an increase in respiration in the biological community (de Souza *et al.,* 2017). Increased respiration is coupled with a decrease in the capacity of water to dissolve oxygen under warm conditions (Arora & Keshari, 2022). The amount of dissolved oxygen in clean flowing waters is usually in the range of 7.6mg/L – 14.6mg/L for 30℃ – 0℃ temperature.

2.1.4 Sediment Oxygen Demand (SOD)

This is made up of biological sediment demand (BSOD) and chemical sediment oxygen demand (CSOD). This is the rate of removal of dissolved oxygen as the biodegradation of organic matter in streambed sediments. SOD creates oxygen deficits in water bodies by reducing the amount of available oxygen in the water column (Chukwuma, *et al.,* 2024). SOD can be a significant percentage of the total oxygen uptake in the aquatic systems (Omole *et al.,* 2019). Measurements of SOD give indication about decomposition rates of settling detritus and regeneration rates of nutrients from the sediment (remineralization) (Kalburgi *et al., 2021*).

2.2 Re-aeration Rate

The re-aeration rate, defined as the net mass flux of oxygen from air to water, can be larger than either oxygen production by photosynthesis or consumption by respiration/oxidation (Sattar *et al.,* 2019), making it a critical control on trends in dissolved oxygen concentration. The absorption of oxygen from the atmosphere is normally assumed to be a first-order process i.e. the rate of absorption is directly proportional to the dissolved oxygen deficit (Infusino & Macario, 2017). For re-aeration to occur, oxygen gas must be transported across the air and water-side boundary layers (Khdhiri *et al.,* 2017). For a poorly soluble gas such as oxygen, the processes regulating exchange on the water-side limit re-aeration rates.

Fig 2.1 shows schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations.

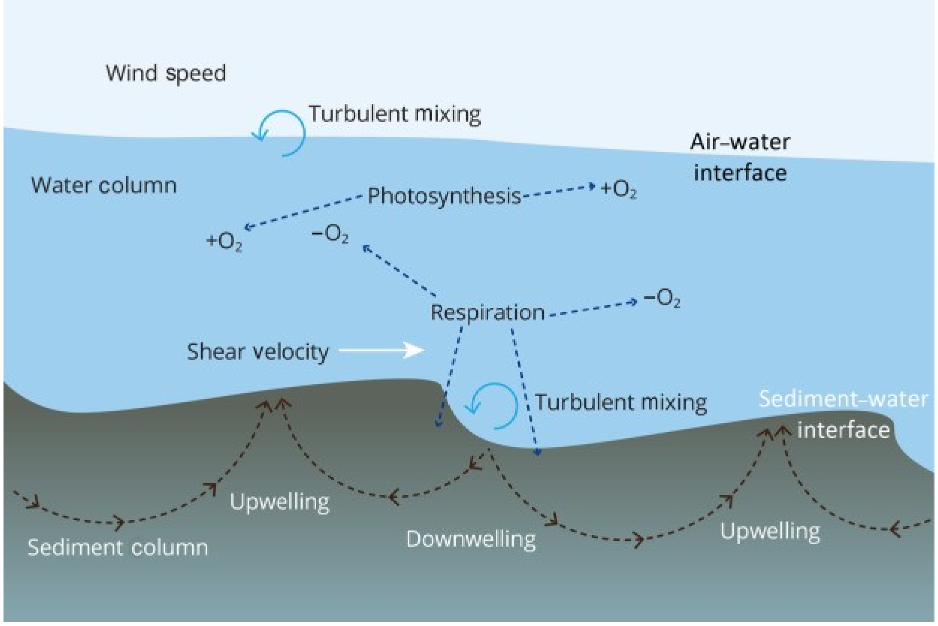


Figure 2.1 Schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations.

Source; (Khdhiri *et al.*, 2017).

Re-aeration rates are usually modeled as the product of a re-aeration coefficient and the oxygen deficit given by the difference between saturated oxygen concentration, which occurs at the water surface, and oxygen concentration below the water-side concentration boundary layer (Wallis *et al.,* 2021). Estimation of the re-aeration coefficient is a major challenge in modeling stream oxygen balance (Lakshmi & Madhu, 2020). Empirical equations based on repeat measurements at multiple sites have related re-aeration coefficient to wind speed, flow velocity, water depth, boundary roughness, and streams slope as proxies for flow turbulence (Baylar *et* *al.,* 2019). However, such models perform poorly when transferred to different sites (Wilson, G. T., & Macleod, 2018).

2.3 Re-aeration Process.

The change in the oxygen deficit in a river is a function of the existing deficit and the re-aeration coefficient. The re-aeration coefficient K_2 is a very important parameter that cannot be overlooked in the determination of maximum organic matter that can be assmimilated by a river in a case of minimum dissolved oxygen concentrations. Because vertical transfer of dissolved oxygen within the water column is rapid relative to transfer across the thin water-surface film, surface transfer of gases can be considered a first order process for the entire depth of the water column (Akatah *et al.,* 2023). Generally speaking, equilibrium or non-equilibrium conditions depend on the chemical potential of the considered species within the phase involved and are often expressed through the concept of fugacity (Al-Zubaidi *et al.,* 2023).

However, mass transfer between phases must be treated differently from the process of simple molecular diffusion, since the diffusion path distance is largely dependent on the characteristics of transport of macroscopic molecules within the phases, and in particular, on the type of flow near the interface. In fact, since the bulk flow of natural water bodies is characterized by its turbulence, turbulence should be considered. A boundary layer is developed in which mass transport takes place through a combination of both turbulent and molecular diffusion resulting from the movement between phases. Molecular diffusion is said to occur near the interface, where a viscous sub-layer exists, while at some distance away from the interface, mass transfer is by turbulent or eddy diffusion. If one phase is rigid in space with respect to another, damping of eddy motion could occur at the interface resulting in low turbulence.

2.4 Diurnal Upstream-Downstream Dissolved Oxygen Change Technique For Determining Whole-Stream Metabolism In Streams.

Marzolf et.al (2015) describes a method that has been widely adopted for the measurement of the metabolism of the ecosystem in small streams. However, the equation used for determining the re-aeration flux of oxygen through the water's surface has proven to be incorrect.

The equation provided by Marzolf (Marzolf *et.al,* 2015)

Re-aeration flux= DO_{defict}* $e^{-K_{oxygen}*T}$ 2.7

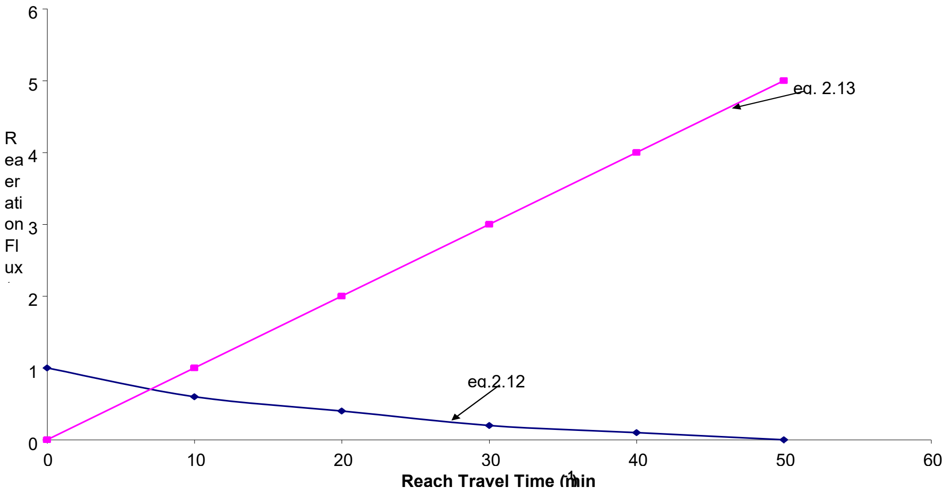
Where;

$DO_{deficit}$ is the difference between dissolved oxygen concentration at 100% and the observed concentration measured in mg/L,

K_{oxygen} is the reaeration coefficient determined using injections of propane to simulate the dynamics of oxygen measured in min^{-1} and

T is the travel time along a specific reach measured in min^{-1}.

Let us consider a stream with re-aeration coefficient K_{oxygen} of 0.07min^{-1} and a constant dissolved oxygen deficit of +1.0mg/L. From equation 2.41, the oxygen flux from a parcel of water during ten minutes of travel down the reach will be 0.497mg/L whereas the flux from the same parcel of water during 60 minutes of travel will be 0.015mg/L. Hence, with identical conditions and the form of equation 2.41, large fluxes of dissolved oxygen will be observed in short reaches than longer reaches. Fig 2.3 shows Variation of Reach Travel Time with Reaeration Flux.



Source; (Marzolf et.al, 2015)

Figure 2.3. Variation of Reach Travel Time with Reaeration Flux

The use of Marzolf's equation may result in substantial negative metabolism during the day and positive net metabolism at night in streams with high re-aeration coefficients. (Thyssen & Erlandsen, 2020). They also pointed out an error in Marzolf’s equation stated as equation 2.41 for calculating re-aeration flux of oxygen over the study reach. The equation used in the calculation of re-aeration flux in the determinations of stream metabolism (de Souza *et al.,* 2020) is given as;

$$Reaeration\ flux = DO_{deficit} \times (1 - e^{-k_{oxygen} \times T}) \qquad 2.8$$

The problem of the erroneous drastic regression in re-aeration as time travel is increased as in equation 2.41 has been eradicated in equation 2.45. However, equation 2.45 is not without limitation as it is not suitable for scenarios in which the dissolved oxygen concentration in a parcel of water is influenced by more than one process (e.g., re-aeration and metabolism) as it flows through the reach in study. Respiration is the balancing factor of the $DO_{deficit}$ in many streams as it flows downstream. In such streams, the use of equation 2.45 above substantially underestimates reaeration flux. The underestimation of the reaeration flux is much higher in streams with relatively high values of k_{oxygen} and (or) relatively long average water travel times. Young and Huryn (1998) propose that the equation below be used to calculate re-aeration flux:

$$Reaeration\ flux = DO_{average\ deficit} \times k_{oxygen} \times T \qquad 2.9$$

Where;

$DO_{deficit}$ is the average $DO_{deficit}$ upstream and downstream of the reach in study.

This equation is similar to that used in traditional single-station and two-station analysis of metabolism where the re-aeration coefficient,k_{oxygen} is multiplied directly by the oxygen deficit, $DO_{deficit}$ to determine the reaeration flux of oxygen (Ranjith *et al.,* 2021). Multiplication of travel time (T) allows the calculation of total oxygen flux (mg/L) along the reach, which then can be used to determine metabolism using equation provided by Marzolf et.al (2015).

In conditions where the dissolved oxygen deficit is subject to substantial change along the study reach, it is advised to use the mean of the dissolved oxygen deficit upstream and downstream

$$Reaeration\ flux = \frac{(DO_{deficit1} + DO_{deficit2})}{2} \times k_{oxygen} \times T \qquad 2.10$$

Where;

$DO_{deficit1}$and$DO_{deficit2}$ are the estimated dissolved oxygen deficits for a parcel of water flowing in the reach under study. This equation makes the assumption that the change in dissolved oxygen deficit is linear during transit given that the processes that may contribute to a short-term shift in dissolved oxygen deficit are multiple and independent. Such processes include temperature, respiration and photosynthesis.

2.5 Measurement of The Surface Water Re-aeration Coefficient Using Krypton (Kr) As A Gas Tracer.

The re-aeration coefficient is said to vary from river to river due to various factors such as climate and flow condition among others. Numerous researchers have investigated gaseous tracer techniques as a means of measurement of the re-aeration coefficientK_2 . Predominant methods involved the dosing of open water systems with applied radioactive gas tracers such as Kr-85. A major deterrent of this technique is the issue of licensing and handling of radioactive materials in the study of river re-aeration. Noble gases have the advantage of low natural ambient levels, inert non-reactive non-sorbing character, low molecular diffusion coefficients, non-toxicity and absence of taste, odor and color.

The tracing technique is dependent on the behavioral dissolution similarity of Kr andO_2 . Kr contained in water escapes to the atmosphere across the air-water interface in a way which is essentially the reverse of $\mathrm{O_2}$mass transfer from the atmosphere into the water. The primary source of Kr is the artificial release and its only escape mechanism is to diffuse into the atmosphere and as such, it may be sued to quantify the gaseous mass transfer process and compute the re-aeration coefficient($\mathrm{K_2}$).

2.6 Study Areas

One of the streams studied is the Oshika stream/lake. The stream lies near the Oshika village situated between Ahoada and Mbiama in Ahoada West Local Government Area, 75km from Port Harcourt along East-West Road. The geographic of the area consists of a tropical rain forest with Niger flood plains and seasonal swamp forest. It is a fresh water swamp having farm land on the dry land on which oil palm, oranges, pear and coconut trees are dispersed. Loam or clay loam is the characteristic soil in the area and sometimes a mixture with clay and silt. In times of rain, the lake flows and is emptied into a floodplain at about a distance of 8km from Oshika village. The water lies relatively quiescent in the lake when there is no surface water contribution. The lake is stagnant as there is no flow in the dry season and the water trapped in the dry land is adopted as ponds for traditional fishing and harvest.

The Otammiri River is located in Imo State, flowing primarily through the Owerri area. It is situated to the northeast of the Ahoada region and serves as a key water source for local communities. Large vegetation covers both sides of the river, greatly contributing to the biodiversity nature of the area. It is also vital for agricultural irrigation, making it an important resource for the surrounding communities.

The Adada River flows through Enugu State and is known for its scenic beauty and clear waters. It is located to the east of Oshika Stream, near the towns of Adada and Nsukka. The surrounding communities include Adada and Nsukka. The river supports a rich biodiversity, with surrounding vegetation providing essential habitats for various wildlife. Locals rely on this river for drinking, irrigation and fishing.

River Kaduna is one of Nigeria's major rivers, flowing through Kaduna State. The river lies to the northwest of the Oshika Stream. It is a very culturally and economically important water body for the communities surrounding it, including the city of Kaduna. This river provides ample opportunities for several farming activities, supplying water for household and fishing activities, and irrigation. The banks are often lined with agricultural land, although the river does suffer from challenges related to sedimentation, pollution, and land-use change.

2.7 Commonly Used Equations for Estimating Re-aeration Coefficients

In the determination of stream re-aeration coefficients, it is important to take into consideration the physical and hydraulic properties of the stream. With the exemption of the Tsivoglou and Neal (1976) equation, nineteen commonly used equations for computing the re-aeration coefficient need to determine the mean stream velocity. The 19 commonly used re-aeration coefficient estimating equations are as follows:

O'connor and Dobbins (1958),

$$K_2 = 12.81\frac{V^{0.5}}{D^{1.5}}; \qquad 2.11$$

Churchill and others (1962),

$$K_2 = 0.03453\frac{V^{2.695}}{D^{3.085}SL^{0.823}}; \qquad 2.12$$

Churchill and others (1962),

$$K_2 = 11.57\frac{V^{0.969}}{D^{1.673}}; \qquad 2.13$$

Krenkel and Orlob (1963),

$$K_2 = 234.5\frac{(V\,SL)^{0.404}}{D^{0.66}}; \qquad 2.14$$

Owens and others (1964),

$$K_2 = 23.23 \frac{V^{0.73}}{D^{1.75}}; \qquad 2.15$$

Owens and others (1964),

$$K_2 = 21.73 \frac{V^{0.67}}{D^{1.85}}; \qquad 2.16$$

Dobbins (1965),

$$K_2 = 116.6 \frac{1+F^2}{(0.9+F)^{1.5}} \frac{(V\ SL)^{0.375}}{D} \coth[\frac{4.10(V\ SL)^{0.125}}{(0.9+F)^{0.5}}; \qquad 2.17$$

Where;

Coth is the hyperbolic cotangent of the angle in radians,

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

$$F = \frac{V}{(g\ D)^{0.5}}, \qquad 2.18$$

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

Langbein and Durum (1967),

$$K_2 = 7.61 \frac{V}{D^{1.33}}; \qquad 2.19$$

Isaac and Gaudy (1968),

$$K_2 = 8.62 \frac{V}{D^{1.50}}; \qquad 2.20$$

Cadwellader and McDonnell (1969),

$$K_2 = 336.8\frac{(V\ SL)^{0.5}}{D};\qquad 2.21$$

Negulescu and Rojanski (1969),

$$K_2 = 10.91(\frac{V}{D})^{0.85};\qquad 2.22$$

Thackson and Krenkel (1969),

$$K_2 = 24.94\frac{(1+(F)^{0.5})u^*}{D};\qquad 2.23$$

Where F is the Froude number,

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

$u^* = (g\ D\ SL)^{0.5}$; 2.24

Padden and Gloyna (1971),

$$K_2 = 6.87\frac{V^{0.703}}{D^{1.054}};\qquad 2.25$$

Bennett and Rathbun (1972),

$$K_2 = 106.10\frac{V^{0.413}SL^{0.273}}{D^{1.408}};\qquad 2.26$$

Bennett and Rathbun (1972),

$$K_2 = 20.19\frac{V^{0.607}}{D^{1.689}};\qquad 2.27$$

Parkhurst and Pomeroy (1972),

$$K_2 = 48.39\frac{(1+0.17F^2)(V\,SL)^{0.375}}{D};\qquad 2.28$$

Bansal (1973),

$$K_2 = 4.67\frac{V^{0.6}}{D^{1.4}};\qquad 2.29$$

Tsivoglou and Neal (1976),

$$K_2 = 1.296\frac{dh}{dT};\qquad 2.30$$

Where dh is the change in water-surface elevation between the beginning and ending points of the reach measured in feet and dT is the change in centroid travel time between the beginning and ending points of the reach measured in hours and Smoot (1987),

$$K_2 = 683.8\frac{V^{0.5325}SL^{0.6236}}{D^{0.7258}}\qquad 2.31$$

2.8 The Indian K_2 model

The coefficient of re-aeration model developed in some water bodies in India is as follows (Jha *et al.*, 2001):

$$K_2 = \frac{5.792V^{0.5}}{H^{0.25}}\qquad 2.32$$

Where;

V is the velocity of stream flow in m/s and H is the hydraulic radius measured in meters (m). the Arrhenius constant which is a conversion factor incorporated in the American k_2 to allow for variation in the rate of re-aeration at different temperature is devoid in this model. The model has in-built changes in temperature which have already been pre-determined. It is paramount that the sampling process is carried out at all times of the year in order to show the significance of the variation in temperature on the atmospheric DO dynamics. This will help produce a model that is free from conversion errors by imploring the use of Arrhenius constant. The Indian model was not only derived from first principles but is already in use such that other recent works have been built on it. (Baylar *et al.,* 2019). In the course of the study, the Indian team gained access to 270 field data sets over a one year period from the Kali river. Testing of the predicted eleven re-aeration equations were carried out. From field survey data, consideration was given to factors such as bed slope, mean stream velocity, friction factor, flow depth and Froude number. The k_2 values computed from these predictive equations were compared with the k_2 values observed from field measurements (Wilson & Macleod, 2018). Methods of estimating errors such as Standard error (SE), mean multiplicative error (MME), normal mean error (NME) and correlation statistics were implored in evaluating how accurate the predictive equations are. It was observed that the equations developed by Smoot *et al*., (2021) and by Cadwallader and McDonnell, (2015) produced comparatively better results than all the predictive models considered. Later on, Jha *et al*., (2019) produced their customized predictive equation by the use of a least-square algorithm for the Kali river after refining the better models. The use of the least-square algorithm reduced the errors in estimates and shows a better correlation between observed and calculated re-aeration coefficients. By this method, the equation is

$$k_2 = C_e \frac{\Delta L}{t_f} \qquad 2.33$$

Where;

ΔL is the change in surface elevation, L; t_f is the time of travel,T; and C_e is the escape coefficient given as $0.177 m^{-1}$ at 20℃.

It was observed by a review of the Smoot *et al*. (2021) and Cadwallader and McDonnell (2022) models that the use of three repressors namely slope, velocity and hydraulic radius were adopted in the prediction procedure of k_2 while two of the regressors namely velocity and hydraulic radius were adopted in the Jha *et al*., (2019) model.

2.9 The Chilean k_2 Model

Bachelor and Laze (2015) presented the results of the modeling experiments performed by them in Chile. They expressed their opinion that the reason for the variations in $k_2$models all over the world could be attributed to the fact that there does not exist a generally accepted and clear criterion to determine which formulation is to be adopted in the modeling the quality of water of any particular river. Rivers in Chile are Mountain Rivers with large amounts of granular sediments, rocky beds filled with potholes containing majority of the pollutant load resulting from the discharge of domestic and industrial wastes into the rivers as reported by them. They produced two k_2 model equations arising from these peculiarities, one for slight slope rivers which is given as:

$$k_2 = \frac{10.046U^{2.696}}{H^{3.902}} \qquad 2.34$$

and the other for medium slope rivers given as:

$$k_2 = \frac{1.923U^{1.325}}{H^{2.006}} \qquad 2.35$$

Where;

U is the mean stream velocity measured in m/s and H is the mean stream depth measured in meters, m.

2.10 The Nigerian $\mathbf{k_2}$ Model

In Nigeria, scanty research has been done in this regard. (Thyssen & Erlandsen, 2020). For Amadi creek in Port Harcourt, Rivers State, Nigeria, Agunwamba *et al*., 2007 computed the re-aeration coefficient k_2 as:

$$k_2 = \frac{11.6325U^{1.6954}}{R^{0.0016}} \qquad 2.36$$

Where: U is the velocity of stream flow measured in m/s and R is the stream hydraulic radius measured in metres, m.

2.11 Model Advancement in the Determination of Coefficient of Re-Aeration

O'connor and Dobbins (2021) equation has been the base on which existing models for determination of re-aeration coefficient were developed. The equation is of the form

$$K_2 = \frac{aU^b}{H^c} \qquad 2.37$$

Where;

K_2 is the reaeration coefficient, a, b and c are constants, U is the river velocity in m/s and H is the river depth in m.

From (Chukwuma *et al.,* 2024) Thomas nomograph like in the case of BOD and DO equation may be used in the computation of dissolved oxygen. There have been proposals of different models for predicting the coefficient of re-aeration. Churchill *et al*., (1962) model was expressed as:

$$K_2 = \frac{5{,}026U^{0.969}}{H^{1.673}}(1.024)^{T-20} \qquad 2.38$$

Where T is the temperature (℃)

In Stephen and Lazzo (1994) study on water quality modeling of Nitra River (Slovakia) derived the following equation

$$K_2 = \frac{12.96U^{0.5}}{d^{1.5}} \qquad 2.39$$

The process of re-aeration can be handled in various ways. In each of these methods, depth and average velocity of the river is taken into consideration in the computation of the re-aeration coefficient. O'connor and Dobbins developed an equation which is suitable for low velocity streams (Omole *et al.,* 2019). Their reparation rate is of the order

$$\frac{dO_2}{dt} = K_2[O_2{}^{*} - O_2] \qquad 2.40$$

For the Nitra River, the following model was proposed by Stephen and Laszlo

$$K_2 = \frac{12.96U^{0.5}}{d^{1.5}} \qquad 2.41$$

In the verification of a re-aeration model in streams, both from the department of Hydraulic and Environment Engineering, University of Napoli, Italy, Carlo and Paola (2022) came up with the re-aeration coefficient of a river to be

$$K_2 = \frac{3.93U_{0.5}}{h^{1.5}} \qquad 2.42$$

2.12 Re-Aeration Coefficient Determined From Agitated Water Tank Experiment

Adequate characterization of the re-aeration coefficient is very necessary to be able to properly quantify the rate of oxygen transfer across the air water interface. The rate of oxygen transfer is governed by the hydrodynamics of the liquid side region. In other words, the approach to determine the re-aeration coefficient requires the characterization of such hydrodynamics. The transfer of gas in flumes demand channel sufficiently long to have gas concentration differences that is much greater than the uncertainties associated with the process of measurement. To be able to overcome this limitation, some researchers have been able to utilize recirculating flumes or moving bed flumes. Long residence time can be achieved in tanks containing water which has been agitated by means of oscillating grids. Agitation by means of One jet or several small Jets has also been reported. When we talk about Low solubility gases, such as oxygen dissolved in water, the liquid side controls the gas transfer process across the air water interface. Normally, the gas transfer rate can be computed from:

$$F=K(C_s - C_B) \qquad 2.43$$

From the formula above, F is given as the time- space flux per unit area across the interface, C_s and C_B are the saturated and bulk concentration of the dissolved gas respectively; K is a global gas transfer coefficient. So many theories have been proposed to relate K with the properties of the dissolved gas, the flow and the liquid. The first theory was the film theory proposed by Nerst in 1904. This theory states that there is a thin film at each of the free surface where the mass transfer is molecular. The films have a constant thickness and are not transported by the flow. Outside of these films, the transfer can be characterized as turbulent. According to this theory, K is proportional to the molecular diffusion coefficient,d. Later on in 1935, Higbie assumed that when the fluid at the free surface has reached a certain“ age”, it is replaced by fluid parcels coming from the bulk. In 1951, Dankwarts (1951) proposed the surface renewal theory in which the interface is composed by elements of fluids with a residence time distribution given sexp(-st), where s is the mean surface renewal rate, t is the time. In accordance to the surface renewal theory, $K_a\sqrt{D_s}$. At this level, the problem remains unsolved as a result of the fact that s is still unknown. To determine s, a number of conceptual theories have been developed. Fortescue and Pearson (1967) proposed the large eddy model in which

$$S\alpha\frac{U}{L} \qquad 2.44$$

Where L is the characteristic length of the largest eddies, U is the characteristic velocity. For this model, it is possible to show that

$$\frac{K}{U_*}\alpha S_c{}^{-\frac{1}{2}}R_e{}^{-\frac{1}{2}} \qquad 2.45$$

Equation 2.95 is defined in terms of the parameters usually used in open channel flows, i.e., the shear velocity U, and the flow depth, H. $R_e = HU_*/V$ and $S_c = \frac{v}{D}$ are the Reynolds and Schimdt numbers respectively, and v is the kinematic viscosity.

2.13 Field Verification for Re-Aeration Models in Streams.

In recent developments the two film theory has been addressed to define the thickness of a liquid film. Two approaches were taken into account in which the first approach shows a comparison between molecular and turbulent diffusivity, while the second one relates δ to smaller eddies in the flow according to Kolmogorov micro-length scale (Kalburgi *et al.,* 2021)

Moreover, improving a previous paper (Rao & Kumar, 2017), the thickness δc of the concentration boundary layer at air-water interface with the bottom classic laminar sub-layer, the latter lies on a solid boundary, whereas the former borders on the interface that, due to surface tension, could be considered as semi-solid boundary.

Model basic assumptions is therefore, that there exists an analogy between the bottom and the water surface; the former has an infinite surface tension, while the latter could be assumed as a wall moving concurrent with a finite value of the surface tension.

Thus, firstly the velocity distribution in the laminar layer near the water surface could be defined starting from the velocity distribution in the laminar layer near the bottom which is well known. If Newton expression for shear stress $\tau = \mu\left(\frac{du}{dy}\right)$ is equated to the linear law $\tau = \tau_0(\frac{y}{h})$, where y is the vertical distance from the air-water interface introducing the frictional velocity $\mathrm{U}^2 = {}^{\tau_0}/_{\rho}$, it could be obtained from:

$$\frac{\mathrm{du}}{\mathrm{dy}} = \frac{\mathrm{U}^2}{\mathrm{v}}\frac{\mathrm{y}}{\mathrm{h}} \qquad 2.46$$

Integrating equation 2.103, near the surface water, a non-dimensional distribution is defined as:

$$\frac{\mathrm{U_0 - U}}{\mathrm{U^*}} = \frac{\mathrm{hU^*}}{2}\left(\frac{\mathrm{y}}{\mathrm{h}}\right)^2 \qquad 2.47$$

Where $\mathrm{U_0}$ is the velocity at air- water interface is as already stated. Since in a wide rectangular section, shear stress $\tau_0 = \mathrm{yhJ}, \mathrm{U}^{*2} = {}^{\tau_0}/_{\rho}$= ghJ and substituting in equation &;

$$\mathrm{U_0 - U} = \frac{\mathrm{gJ}}{2.\mathrm{v}}\mathrm{y}^2 \qquad 2.48$$

At the end, the proposed model is

$$K_L=\frac{{D_m}^{2/3}y^{1/3}}{Re_{m-t}\;\bar{y}\Big/(\frac{gJ}{2g})^{1/3}} \qquad 2.49$$

J is piezometric slope; Re_{m-t} is a mass transfer Reynolds number.

The proposed model has been verified using a large amount of field data; a data-based re-aeration rate K_a measure using tracer-gas methods in streams throughout the United States has been recently prepared by United States Geological Survey (USGS), which has collected these data over may years; the database was kindly provided (Sattar *et al.,* 2019). The USGS database includes K_a values measured for 493 independent researchers on 166 streams in 23 states of USA.

O'Connor- Dobbins equation starts from the assumption that the renewal rate could be approximated by depth, h, and gives:

$$K_a = 3.93\frac{U^{0.5}}{h^{1.5}} \qquad 2.50$$

While Gibbs-Owens is similar but possesses different power and power coefficients. Finally, Parkhurst-Pomeroy semi-empirical model is based on an energy dissipation model and a molecular diffusion model. For the more O'Connor-Dobbins and Gibbs-Owens equation have a different and narrow field of application; the former was verified originally for deep and slow streams, while the latter is suggested to hold for shallow and fast moving streams with $h < 0.70m$.

Results show that O'Connor-Dobbins and Parkhurst-Pomeroy formulae tend meanly to underestimate re-aeration rate while Gibbs-Owens gives an unpredictable result; the standard deviation is always not negligible, so that observation and predictions are not well-fitted.

2.14 River Water Quality Modeling

River Water Quality Modeling has become an important means of gaining knowledge, prediction, and management of freshwater ecosystem health. It offers a scientific explanation of how natural events and human activities affect water quality for guidance of policy framers in putting in place proper management strategies. This modern model of water quality can simulate several of the physical, chemical, and biological processes through which river systems respond to pollutant transport, nutrient cycling, and oxygen dynamics. The next section presents the main driving forces, methodologies, and problems of river waters' quality modelling. Water quality models in river systems are developed to simulate the transport of pollutants and other constituents within such aquatic environments. These models use mathematical expressions that describe processes such as advection, dispersion, and biochemical transformations (Wallis *et al.,* 2021).

Among them, one of the widely used methodologies is the one-dimensional advection-dispersion equation that can describe the material transport and dispersion along the trajectory of river flow. Advanced models solve complicated hydrodynamics and interactions of the river-fringe ecosystem, accounting for multidimensional flow fields as given by (Lakshmi & Madhu, 2020). QUAL2K is the most applied model in determining the quality of river water as it is solely designed for rivers and streams through the U.S. Environmental Protection Agency. As a one-dimensional, the steady-state model that accurately simulates important parameters such as dissolved oxygen, temperature, nutrient concentrations, and biochemical oxygen demand under conditions of steady-state flow (Chukwuma *et al.,* 2024).

Even with these limitations, especially in the handling of non-steady-state conditions such as stormwater events, this model was widely applied because it was simple and could model point-source pollution impacts on rivers.

WASP is another powerful tool for water quality modeling. It is a dynamic model that can simulate pollutant transport and fate in both rivers and estuarine environments. WASP integrates the effects of hydrodynamics, pollutant loads, and water chemistry to simulate the transport of contaminants and nutrients in river systems. This model is particularly useful for assessing long-term impacts of nutrient loading and can be adapted for site-specific applications (Al-Zubaidi *et al.,* 2024). MIKE 11, developed by the Danish Hydraulic Institute, DHI, is an integrated system for river and channel modeling, covering hydrodynamics, water quality, and sediment transport. This model can simulate several water quality indicators such as dissolved oxygen, nitrogen, phosphorus, and heavy metals amongst others, as documented by DHI in 2017. It is thus flexible to apply at whatever river scale, from minor streams to major transboundary rivers. In this respect, the model has very wide applications in flood risk management, water resource planning, and environmental impact assessments (Thyssen & Erlandsen, 2020).

Despite such development in modeling techniques, several issues still remain. First, there is a lack of data of the high order and longitudinally-extensive type that is needed for model calibration and validation. Several models use rather sparse data, which could result in large uncertainties regarding predictions of the outcomes. (Ranjith *et al.,* 2021). The second challenge is the complexity of the river systems due to seasonal changes in discharge, land cover, and climatic variations. These demand flexibility and adaptiveness. (Salihu *et al.,* 2020).

2.15 Summary of Literature Review

In this literature, the essential role of re-aeration in preserving water quality in rivers was examined. Re-aeration denotes the process by which air oxygen is absorbed into flowing water, crucial for restoring dissolved oxygen (DO) depleted during the decomposition of organic matter. Multiple models and approaches were analyzed for forecasting the re-aeration coefficient (k2) of rivers based on streamflow attributes. The review emphasizes various critical processes that enhance the overall health of aquatic ecosystems. Biochemical deoxygenation rate of river water and the oxygen replenishment rate were examined, which are essential for evaluating the level of pollution in surface waters. The importance of natural processes were highlighted, including dilution from streams, biological re-oxygenation via photosynthesis, and atmospheric re-aeration.

Omole (2013) presented a shortlist of ten re-aeration constant models for evaluation using various data sets obtained from the Atuwara River in Ota, Ogun State. Table 9 and Table 10 of the appendices show the shortlisted models and the data obtained. This records obtained from literature will further be used to validate the New Model derived in this study.

Notable methods for determining the re-aeration coefficient were assessed, including the renowned O'Connor and Dobbins model and its constraints, especially for non-steady-state situations. Additionally, the N-Model was presented, which was devised throughout the research, and contrasted its outcomes with those of recognized models, including the Parkhurst and Churchill models. The findings indicated that the N-Model yielded precise forecasts of k2 values, implying its utility without the necessity for substantial laboratory experimentation. The research indicates that the re-aeration process is affected by several environmental parameters, such as flow velocity, water depth, and the presence of organic materials. Elevated biochemical oxygen demand (BOD) levels can substantially affect dissolved oxygen (DO) concentrations, endangering aquatic organisms and compromising water quality.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Re-aeration coefficient of some selected rivers obtained from literature

The mean values of data from the following rivers; Otammiri, Adada, Kaduna River and Oshika Lake was determined from the literature and the result tabulated in Table 3.1 below.

Table 3.1: Mean stream flow data of selected rivers obtained from literature (see various sources of the raw data in the appendices)

RIVERS				
PARAMETERS	**OTAMMIRI**	**OSHIKA LAKE**	**RIVER KADUNA**	**ADADA**
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 (^{o}C)	20	28	23	28.2
Re-aeration coefficient (k_2)	0.075	0.069	0.8481	0.85

3.1.2 Map of Study Areas

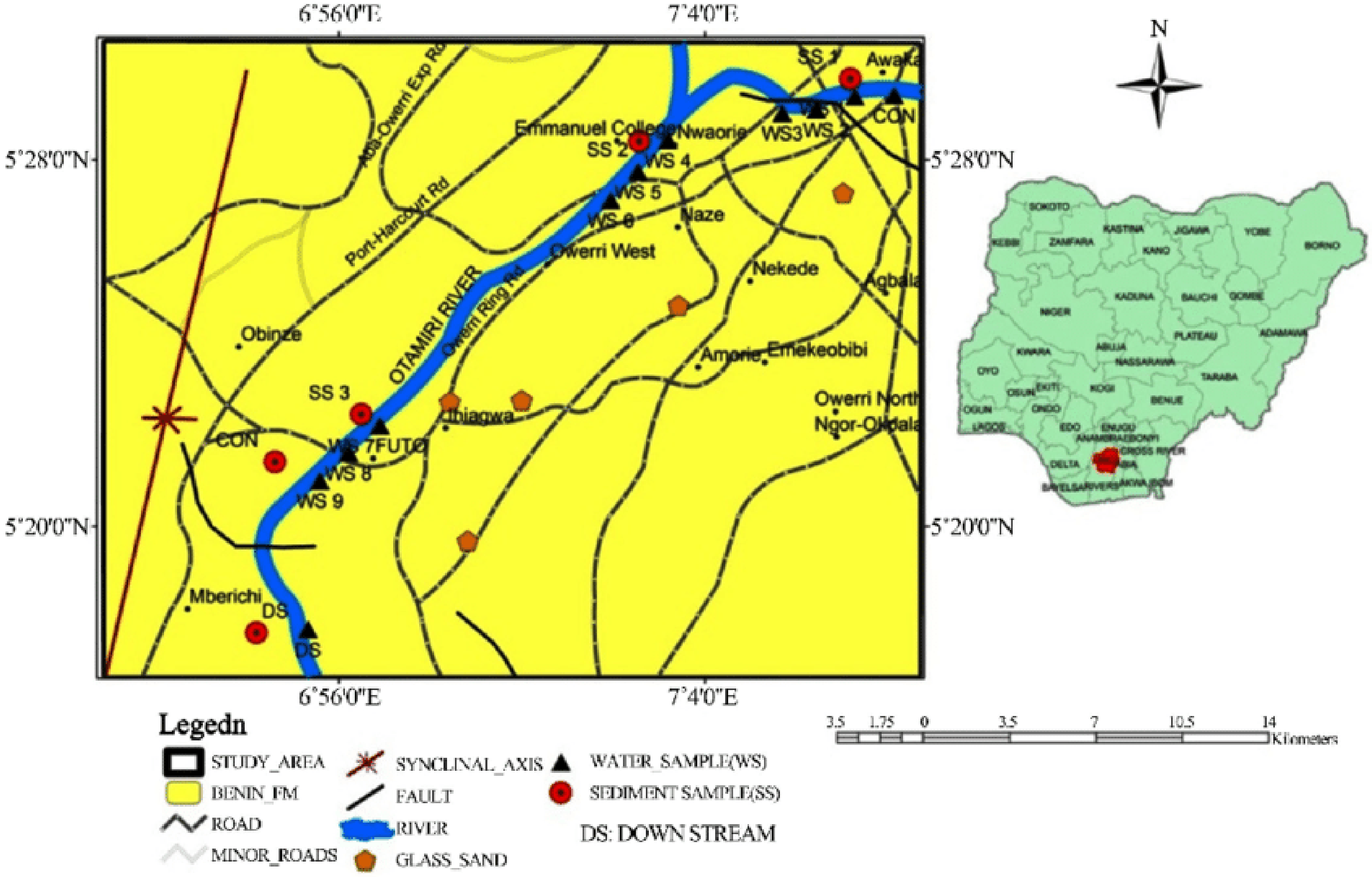


Fig 3.1 Map of Otammiri River

Fig 3.2 Map of Oshika Lake

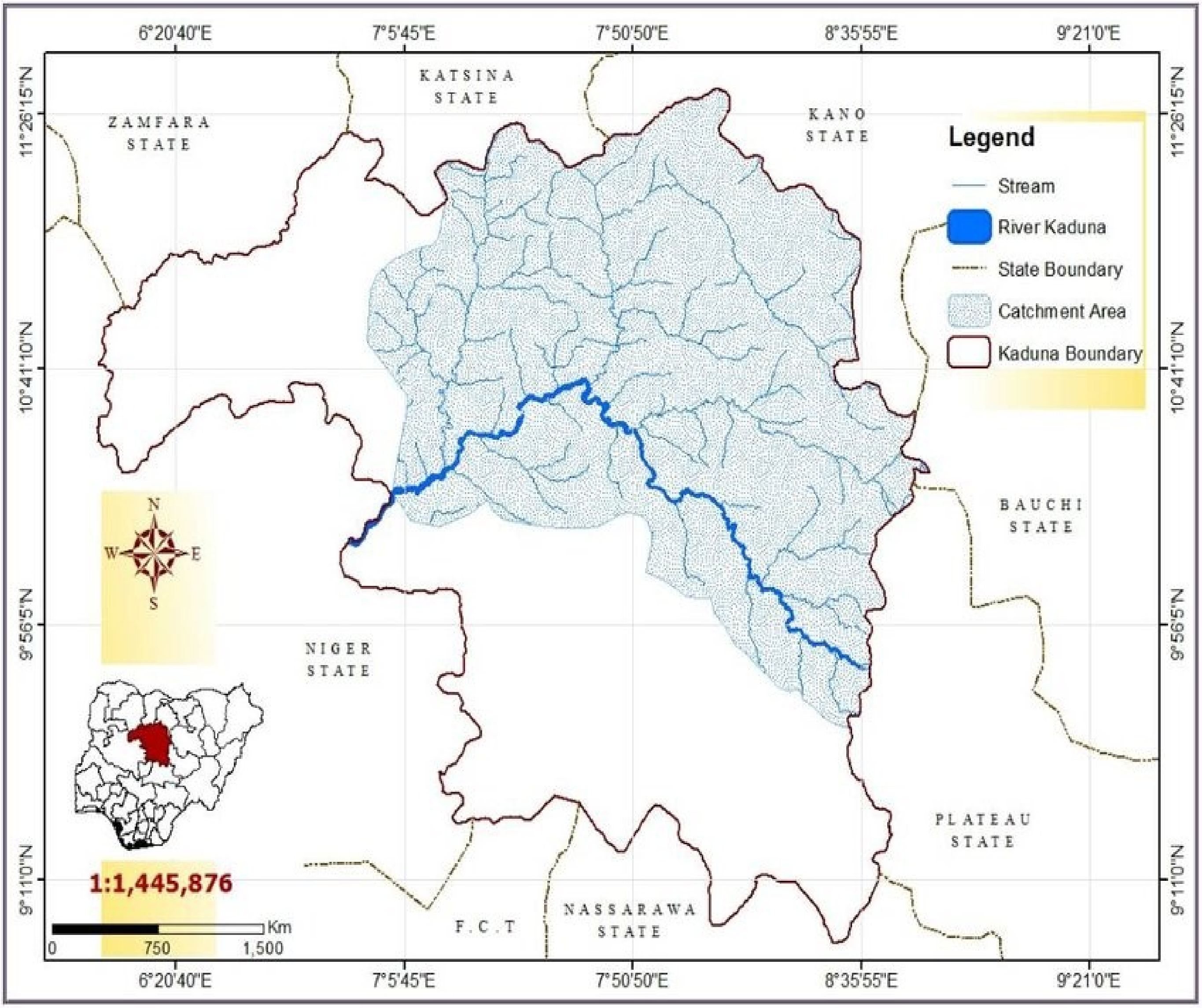


Fig 3.3 Map of River Kaduna

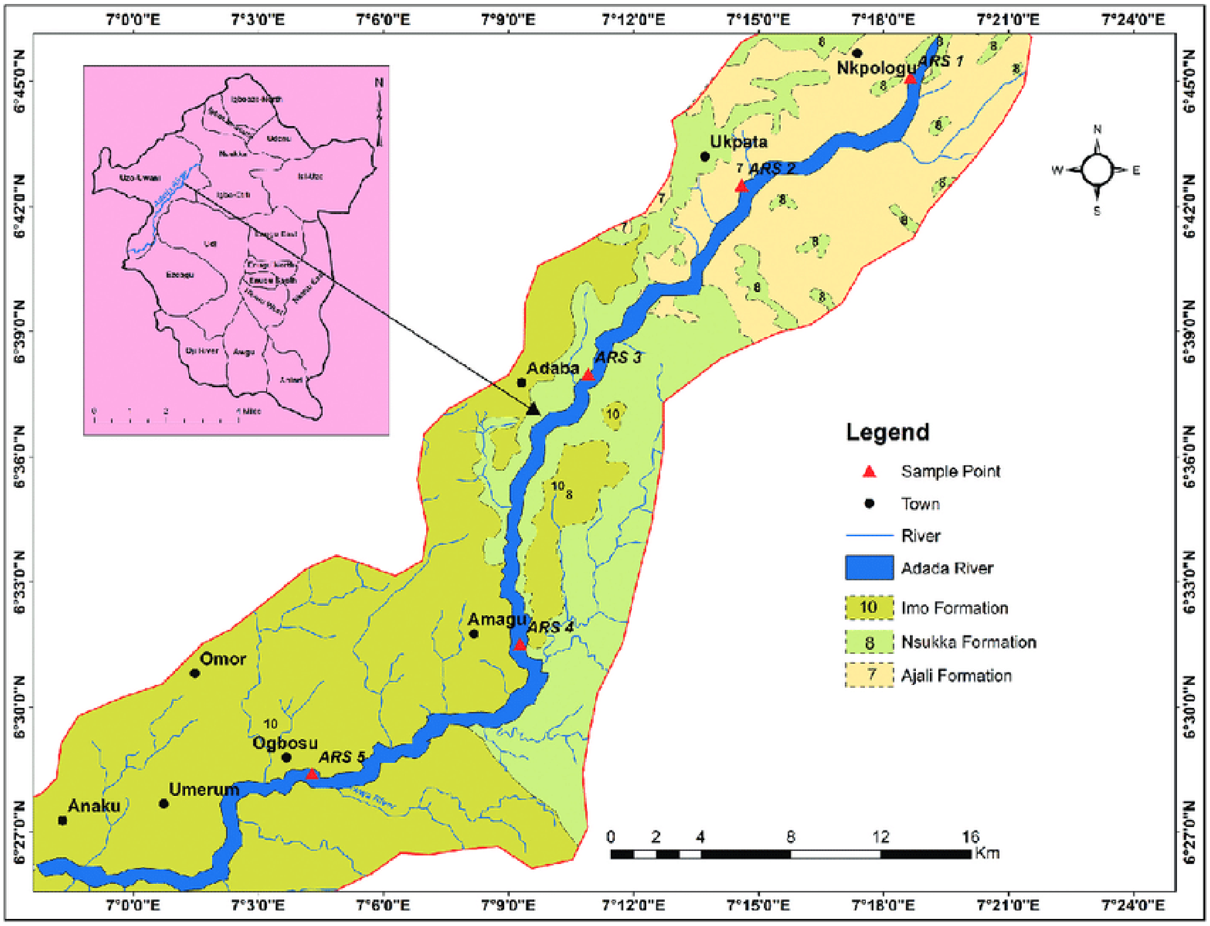


Fig 3.4 Map of River Adada

3.1.3 States And G.P.S Locations of Study Areas

RIVERS	STATES	G.P.S LOCATIONS
Otammiri	Imo	5.20052, 7.01295
Oshika Lake	Rivers	5.07360, 6.56261
River Kaduna	Niger	10.49225, 7.41095
Adada	Enugu	6.47186,7.07724

3.2 Methods

3.2.1 Some Selected Empirical Models for the Determination of Re-aeration Constant

Table 11 shows some of the available re-aeration equations sub-divided into four groups. These groups are based on the number of variables appearing in these equations following the approach adopted by Gualtieri and Gualtieri (2002). These variables represent the physical characteristics of the water bodies, such as velocity, depth, slope, and others that influence the re-aeration rate. Here's a breakdown of what this means:

Grouping Based on Variables:

1. **Group 1 (Simple Models)**: These models use a few variables, often just velocity (U) and depth (D)**.** They are simpler equations and are typically used for a broad range of river systems.
2. **Group 2 (Intermediate Complexity Models)**:

These equations include additional variables, such as hydraulic radius (R)**,** slope (S)**, or** river width in addition to velocity and depth.

3. **Group 3 (More Complex Models)**:

These models introduce even more variables, incorporating factors like Froude number (F) or parameters related to the river's turbulence or flow type. They account for the complexity of larger, more dynamic river systems.

4. **Group 4 (Highly Specific Models)**:

These equations are highly detailed and incorporate unique variables like flume characteristics or non-standard hydraulic properties. They are usually tailored to specific types of water systems or experiments.

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:

$$k_2 = \frac{3.9V^{0.5}\sqrt{(1.037)^{(T-20)}}}{H^{3/2}} \qquad 3.1$$

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.

(Churchill et al.,1962),

$$K_2 = 0.03453\frac{V^{2.695}}{D^{3.085}SL^{0.823}}; \qquad \text{(Ref. 2.12)}$$

Krenkel and Orlob (1963),

$$K_2 = 234.5\frac{(V\ SL)^{0.404}}{D^{0.66}}; \qquad \text{(Ref. 2.14)}$$

Owens and others (1964),

$$K_2 = 23.23\frac{V^{0.73}}{D^{1.75}}; \qquad \text{(Ref. 2.16)}$$

Dobbins (1965),

$$K_2 = 116.6\frac{1+F^2}{(0.9+F)^{1.5}}\frac{(V\ SL)^{0.375}}{D}\coth[\frac{4.10(V\ SL)^{0.125}}{(0.9+F)^{0.5}}; \qquad \text{(Ref. 2.17)}$$

Where;

Coth is the hyperbolic cotangent of the angle in radians,

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

$$F = \frac{V}{(g\ D)^{0.5}}, \qquad \text{(Ref. 2.18)}$$

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

Parkhurst and Pomeroy (1972),

$$K_2 = 48.39\frac{(1+0.17F^2)(V\ SL)^{0.375}}{D}; \qquad \text{(Ref. 2.28)}$$

Thackston and Krenkel (1969),

$$K_2 = 24.94\frac{(1+(F)^{0.5})u^*}{D}; \qquad \text{(Ref. 2.23)}$$

Where F is the Froude number,

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

$$u^* = (g\ D\ SL)^{0.5}; \qquad \text{(Ref. 2.24)}$$

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°C, g is the acceleration due to gravity in m/s^2 ($9.81m/s^2$)

3.2.2 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;

$$K_2 = \frac{xU^y}{D^z} \qquad 3.2$$

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).

How the Equation Works:

- **Velocity effect**: A higher U increases K_2, reflecting that faster rivers mix atmospheric oxygen more efficiently.
- **Depth effect**: A deeper river decreases K_2, as oxygen from the atmosphere has a harder time penetrating deeper water bodies.
- **Calibration**: Field measurements of river depth, velocity, and observed DO levels are used to adjust x, y, and z, which makes the model applicable to specific river systems.

3.2.3 Methods of Obtaining Field Values of Re-Aeration Coefficients (K_2)

The re-aeration coefficient from field values were obtained using the equation

$$K_2 = \frac{\ln(DO_{initial}/DO_{deficit})}{time(days)} \qquad 3.3$$

Where;

K_2 is the re-aeration rate constant,

$DO_{initial}$ is the initial dissolved oxygen and

$DO_{deficit}$ is the difference between saturation dissolved oxygen and the observed dissolved oxygen. (Omole and Longe, 2012).

3.2.3.1 Measurement of Time and Velocity

Along the Oshika stream/lake, twelve sampling stations were set up with the distance under study as 2,400 meters and collection of samples was carried out monthly. The parameters analyzed include: dissolved oxygen (DO), depth, hydraulic radius, velocity and temperature. An electronic clock was used in recording the time at which readings were taken while a current meter was used in the measurement of the stream velocity.

3.2.3.2 Measurement of Temperature

A rope was provided to which a laboratory thermometer was attached and dropped into the stream such that half of the thermometer was under water. Temperature readings were taken off the stem of the thermometer. In all the twelve stations, the temperature readings were simultaneously taken.

3.2.3.4 Determination of distance, depth and width

The Rivers State land and Survey Bureau aided the provision of a scaled map of the area under study. A GPS showing landmarks and measurement was used in determining the position of the Oshika stream/lake. The collection of the sample was carried out downstream at varying interval. The measurement of the depth involves lowering a loaded tape to the lake bed and a tape run across the lake/stream was used to determine the depth.

3.2.3.5 Determination of Dissolved Oxygen

By the use of the Wrinkler method based off the American Public Health Association (APHA) Standard Methods for the Examination of Water and Wastewater and with the aid of a digital titrator, the following procedures were followed;

a) BOD bottle was used in the collection of the sample. To prevent air bubbles from being trapped, the samples were allowed to overflow the bottle for 2-3 minutes. The trapper was inserted right after to prevent air from being trapped in the bottle and severally inverted to mix. After a duration of five minutes, the formed precipitate settled out.

b) The contents of one dissolved oxygen reagent powder pillow were added following the removal of the stopper. After replacement of the stopper without trapping air in the bottle, the bottle was inverted severally to mix. A yellow colored floc dissolved indicating the presence of oxygen.

c) 20ml of the prepared sample was accurately measured and transferred to 250ml Erlenmeyer flask. To a 0.2 Sodium Thio-sulphate titration cartridge was attached a clean straight stem delivery tube twisted into the titrator body. The counter was reset to zero and the tip wiped after the flushing of the delivery tube. Titration of the prepared solution with 0.2 Sodium Thiosulphate was carried out until there was a color change from yellow to colorless in the samples. The number of digits was computed. Calculate digits required ×0.1= mg/l dissolved oxygen. (Adhya, 2023).

3.2.4 Comparison of Results with Already Existing Models:

Statistical Measures of Evaluation

Johnson and Omland (2004) suggested that when the goal of model selection is prediction and when there is no overwhelming support by data for a single model, further model evaluation should be conducted. The aim of model evaluation is to check the level of agreement between measured and simulated data. Recommended statistics for model evaluation are categorized into dimensionless statistics and absolute error index statistics Moriasi *et al*. (2007). Moriasi *et al*. (2007) further recommended that at least one dimensionless statistic and at least one absolute error index should be included in the model evaluation. The Dimensionless statistics include in this study is Nash–Sutcliffe efficiency (NSE), while absolute error statistics include mean absolute error, percent bias (PBIAS), root mean square error (RMSE) and RMSE observation standard deviation ratio (RSR).

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}\left(y_i^{\mathrm{obs}} - y_i^{\mathrm{sim}}\right) \times 100}{\sum_{i=1}^{n}\left(y_i^{\mathrm{obs}}\right)}\right] \qquad 3.4$$

Where y_i^{obs} = observed data and y_i^{sim} = simulated data.

PBIAS value of 0.0 is optimal and indicates accuracy of model simulation. However, negative PBIAS value indicates overestimation in simulation and should be rejected.

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(y_i^{\mathrm{obs}} - y_i^{\mathrm{sim}}\right)^2}{\sum_{i=1}^{n}\left(y_i^{\mathrm{obs}} - \bar{y}\right)^2}\right] \qquad 3.5$$

Where $\bar{y}$ is mean value of the observed data. NSE compares the variance between noise and information. An NSE value between 0.0 and 1.0 is acceptable. However, the model with higher NSE value is preferred in model evaluation.

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\sigma^2} \qquad 3.6$$

Where σ^2 = standard deviation. RSR value of 0 is optimal. The lower the RSR value, the better is the model simulation.

It should be noted that a software analysis of the confidence limit for the models will also be carried out.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1: The re-aeration coefficients data obtained from literature

The re-aeration coefficient data for four rivers namely; Otamiri, Kaduna river, Adada and Oshika lake were obtained from literature and are presented below.

Otammiri River

Substituting the values for the parameters in O'connor's equation, we have;

$$k_2 = \frac{3.9(0.016)^{0.5}\sqrt{(1.037)^{(20-20)}}}{3.501^{1.5}} \qquad 4.1$$

$$k_2 = \frac{0.4933\sqrt{1.037^0}}{6.551} \quad k_2 = 0.0753$$

(Churchill et al., 1962),

$$k_2 = 0.03453\frac{0.016^{2.695}}{3.501^{3.085}0.00005^{0.823}} \qquad 4.2$$

$$k_2 = 0.03453\frac{1.446\times10^{-5}}{0.0138}$$

$$k_2 = 0.03453\times1.048\times10^{-3}$$

$$k_2 = 3.62\times10^{-5}$$

Krenkel and Orlob (1963),

$$k_2 = 234.5\frac{(0.016\times0.00005)^{0.404}}{3.501^{0.66}} \qquad 4.3$$

$$k_2 = 234.5\frac{3.442 \times 10^{-3}}{2.286}$$

$$k_2 = 234.5 \times 1.51 \times 10^{-3}$$

$$k_2 = 0.354$$

(Owens et al., 1964),

$$k_2 = 23.23\frac{0.016^{0.73}}{3.501^{1.75}} \tag*{4.4}$$

$$k_2 = 23.23\frac{0.049}{8.96}$$

$$k_2 = 23.23 \times 5.47 \times 10^{-3}$$

$$k_2 = 0.127$$

Dobbins (1965),

$$F = \frac{0.016}{(9.81 \times 3.501)^{0.5}} \tag*{4.5}$$

$$F = 2.73 \times 10^{-3}$$

$$K_2 = 116.6\frac{1 + (2.73 \times 10^{-3})^2}{(O.9 + 2.73 \times 10^{-3})^{1.5}}\frac{(0.016 \times 0.00005)^{0.375}}{3.501} coth \frac{4.10(0.016 \times 0.00005)^{0.125}}{(0.9 + 2.73 \times 10^{-3})^{0.5}}$$

$$k_2 = 116.6 \times 1.166 \times 1.47 \times 10^{-3} \coth 0.7463$$

$$k_2 = 0.1999 \times 0.9646$$

$$k_2 = 0.193$$

Parkhurst and Pomeroy (1972),

$$k_2 = 48.39\frac{\left(1+0.17\times\left(2.73\times10^{-3}\right)^2\right)(0.016\times0.00005)^{0.375}}{3.501} \quad 4.6$$

$$k_2 = 48.39\frac{1.00\times5.17\times10^{-3}}{3.501}$$

$$k_2 = 48.39\times1.628\times10^{-3}$$

$$k_2 = 0.078$$

Thackston and Krenkel (1969),

$$u^* = (9.81\times3.501\times0.00005)^{0.5}$$

$$u^* = 0.0414$$

$$k_{2=}24.94\frac{\left(1+\left(2.73\times10^{-3}\right)^{0.5}\right)0.0414}{3.501} \quad 4.7$$

$$k_2 = 24.94\frac{0.0436}{3.501}$$

$$k_2 = 24.94\times0.0125$$

$$k_2 = 0.311$$

River Kaduna

Substituting the values for the parameters in the above equation;

Average mean velocity = 0.1975m/s, Average mean depth = 1.33m, Temperature = 23℃, Water surface slope = 0.000306698

Starting with O’connor’s equation,

$$k_2 = \frac{3.9\times0.1975^{0.5}\sqrt{1.037^{(23-20)}}}{1.33^{3/2}} \tag{4.8}$$

$k_2 = 1.078$

(Churchill et al., 1962),

$$k_2 = 0.03453\frac{0.1975^{2.695}}{1.33^{3.085}0.000306698^{0.823}} \tag{4.9}$$

$k_2 = 0.141$

Krenkel and Orlob (1963),

$$k_2 = \frac{234.5(0.1975\times0.000306698)^{0.404}}{1.33^{0.66}} \tag{4.10}$$

$k_2 = 3.841$

(Owens et al., 1964)

$$k_2 = 23.23\frac{0.1975^{0.73}}{1.33^{1.75}} \tag{4.11}$$

$\mathrm{k}_2 = 4.32$

Dobbins (1965),

$$\mathrm{F} = \frac{0.1975}{(9.81\times1.33)^{0.5}} \tag{4.12}$$

F=0.055

$$\mathrm{k}_2 = 116.6\frac{1+0.055^2}{(0.9+0.055)^{1.5}}\times\frac{(0.1975\times0.000306698)^{0.375}}{1.33}\coth\frac{4.10(0.1975\times0.000306698)^{0.125}}{(0.9+0.055)^{0.5}}$$

k_2 =inconclusive

Parkhurst and Pomeroy (1972),

$$k_2 = \frac{48.39(1 + 0.17 \times 0.055^2)(0.1975 \times 0.000306698)^{0.375}}{1.33}$$

k_2 =0.954

Thackston and Krenkel (1969),

$$u^* = (9.81 \times 1.33 \times 0.000306698)^{0.5}$$

$$=0.0633$$

$$k_2 = 24.94 \frac{(1 + 0.055^{0.5})0.0633}{1.33}$$

$$k_2 = 1.465$$

Adada River

Average mean velocity= 0.4084m/s, Average mean depth= 0.758m, Water temperature= 28.2℃, Water surface slope= 0.000202748

Starting with O'connor's equation

$$k_2 = \frac{3.9 \times 0.4084^{0.5}\sqrt{1.037^{(28.2-20)}}}{0.758^{\frac{3}{2}}}$$

$k_2 = 4.383$

Churchill and others (1962),

$$k_2 = 0.03453 \frac{0.4084^{2.695}}{0.7583^{3.085} \times 0.000202748^{0.823}}$$

$k_2 = 7.946$

Krenkel and Orlob (1963),

$$k_2 = \frac{234.5(0.4084 \times 0.000202748)^{0.404}}{0.758^{0.66}}$$

$k_2 = 6.316$

Owens and others (1964),

$$k_2 = 23.23 \frac{0.4084^{0.73}}{0.758^{1.75}}$$

$k_2 = 19.621$

Dobbins (1965),

$$F = \frac{0.4084}{(9.81 \times 0.758)^{0.5}}$$

$F = 0.150$

$$k_2 = 116.6 \times \frac{1 + 0.150^2}{(0.9 + 0.150)^{1.5}} \times \frac{(0.4084 \times 0.000202748)^{0.375}}{0.758} \coth \frac{4.10(0.4084 \times 0.000202748)^{0.125}}{(0.9 + 0.150)^{0.5}}$$

$k_2 = \text{inconclusive}$

Parkhurst and Pomeroy (1972),

$$\mathrm{k_2} = \frac{48.39\big(1 + (0.17 \times 0.150^2)\big)(0.4084 \times 0.000202748)^{0.375}}{0.758}$$

$$\mathrm{k_2} = 1.888$$

Thackston and Krenkel (1969),

$$\mathrm{u}^* = (9.81 \times 0.758 \times 0.000202748)^{0.5}$$

$$\mathrm{u}^* = 0.087$$

$$\mathrm{k_2} = 24.94\,\frac{(1 + 0.150^{0.5})0.087}{0.758}$$

$$\mathrm{k_2} = 3.971$$

Oshika Lake

Average mean velocity = 0.00105m/s, Average mean depth = 2.3m, Water temperature = 28℃, Water surface slope = 2.971×10^{-10}

Beginning with O’connor’s equation,

$$\mathrm{k_2} = \frac{3.9 \times 0.00105^{0.5}\sqrt{1.037^{(28-20)}}}{2.3^{\frac{3}{2}}}$$

$$\mathrm{k_2} = 0.042$$

(Churchill et al., 1962),

$$\mathrm{k_2} = 0.03453\,\frac{0.00105^{2.695}}{2.3^{3.085}2.971 \times 10^{-10^{0.823}}}$$

$$k_2 = 0.00172$$

Krenkel and Orlob (1963),

$$k_2 = \frac{234.5(0.00105 \times 2.971 \times 10^{-10})^{0.404}}{2.3^{0.66}}$$

$$k_2 = 0.00120$$

Owens and others (1964),

$$k_2 = 23.23\frac{0.00105^{0.73}}{2.3^{1.75}}$$

$$k_2 = 0.0362$$

Dobbins (1965),

$$F = \frac{0.00105}{(9.81 \times 2.3)^{0.5}}$$

$$F = 0.000221$$

$$k_2 = 116.6 \times \frac{1 + 0.000221^2}{(0.9 + 0.000221)^{1.5}} \times \frac{(0.00105 \times 2.971 \times 10^{-10})^{0.375}}{2.3} \coth \frac{4.10(0.00105 \times 2.971 \times 10^{-10})^{0.125}}{(0.9 + 0.000221)^{0.5}}$$

$$k_2 = 0.000144$$

Parkhurst and Pomeroy (1972),

$$k_2 = \frac{48.39\left(1 + (0.17 \times 0.000221^2)\right)(0.00105 \times 2.971 \times 10^{-10})^{0.375}}{2.3}$$

$$k_2 = 0.000430$$

Thackston and Krenkel (1969),

$\mathrm{u}^{*} = (9.81 \times 2.3 \times 2.971 \times 10^{-10})^{0.5}$

$\mathrm{u}^{*} = 0.0000819$

$$\mathrm{k}_2 = 24.94 \frac{(1 + 0.000221^{0.5})0.0000819}{2.3}$$

$$\mathrm{k}_2 = 0.000901$$

4.1.2: Derivation of an empirical relationship for predicting re-aeration constant

The derived empirical relationship is equation 3.3 as shown in the methodology.

The model was calibrated as follows;

$$lnK_2 \ = \ lnx \ + \ ylnU - zlnD \qquad 4.11$$

$$-2.590 \ = \ lnx - 4.135y - 1.253z \qquad 4.12$$

$$-0.164 \ = \ lnx - 1.622y - 0.285z \qquad 4.13$$

$$-0.162 \ = \ lnx - 0.895y \ + \ 0.277z \qquad 4.14$$

Solving equations (4.12), (4.13) and (4.14) simultaneously, yield the values of the constants;

x = 9.44, y = 1.921 and z = -2.482, substituting these values in equation (4.11) yields;

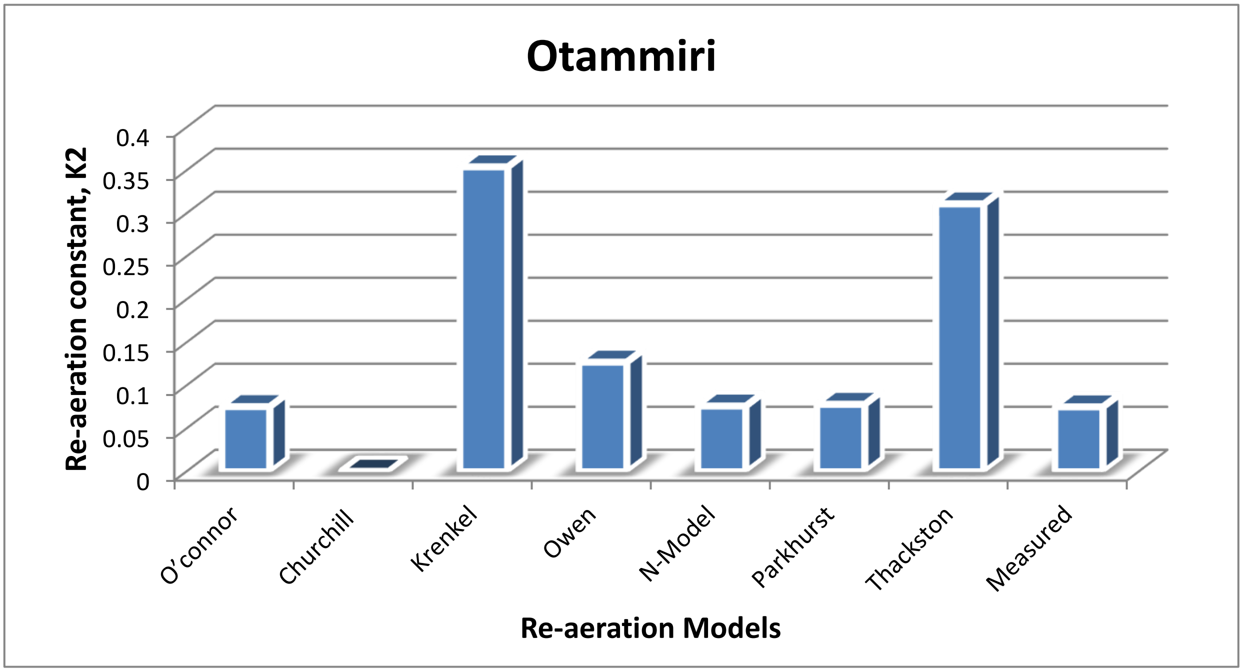
$$K_2 = 9.44 \frac{U^{1.921}}{D^{-2.482}} \qquad 4.15$$

Equation (4.15) is our newly formulated model and will be designated thus as N-Model in this study.

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

The results of the re-aeration coefficients computed with various equations are as shown in Table 4.1 below:

Table 4.1: 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	0.0000362	0.354	0.127	0.076	0.078	0.311	0.075
Kaduna	1.078	0.141	3.841	4.320	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	0.00120	0.0362	0.0041	0.000430	0.000901	0.069

Fig 4.1: Variation of K_2 with Re-aeration models for Otammiri River

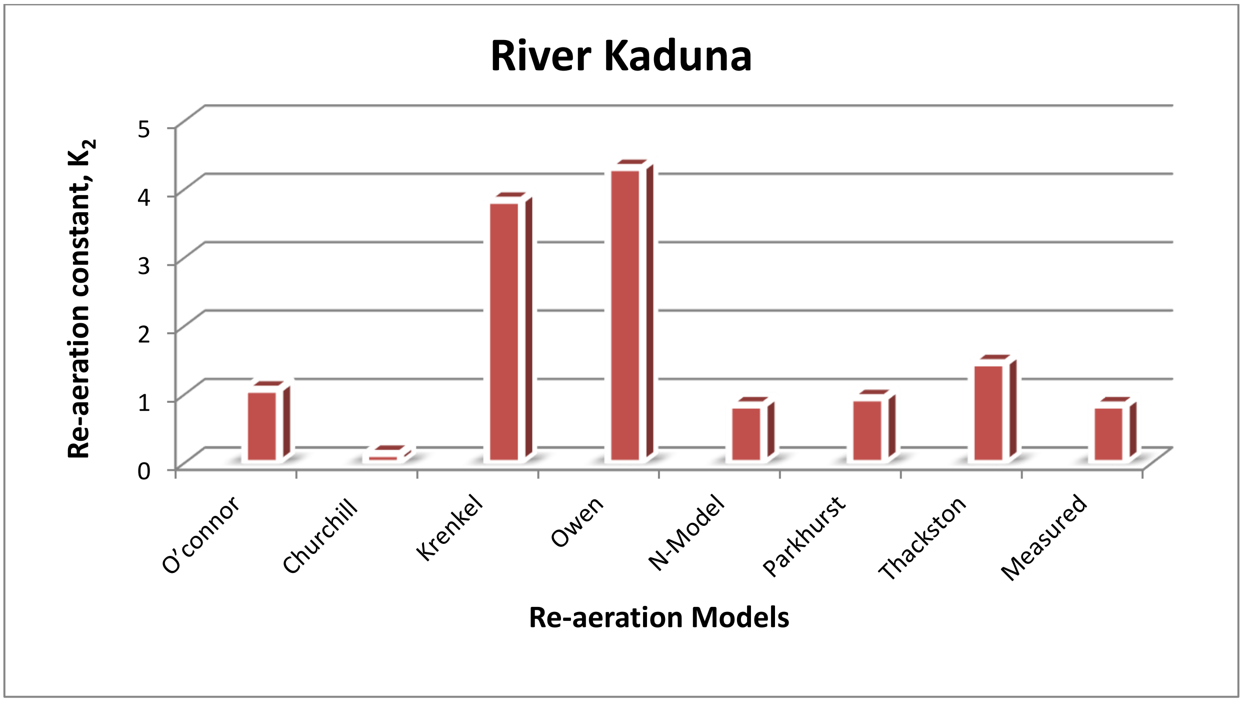


Fig 4.2: Variation of K_2 with Re-aeration models for River Kaduna

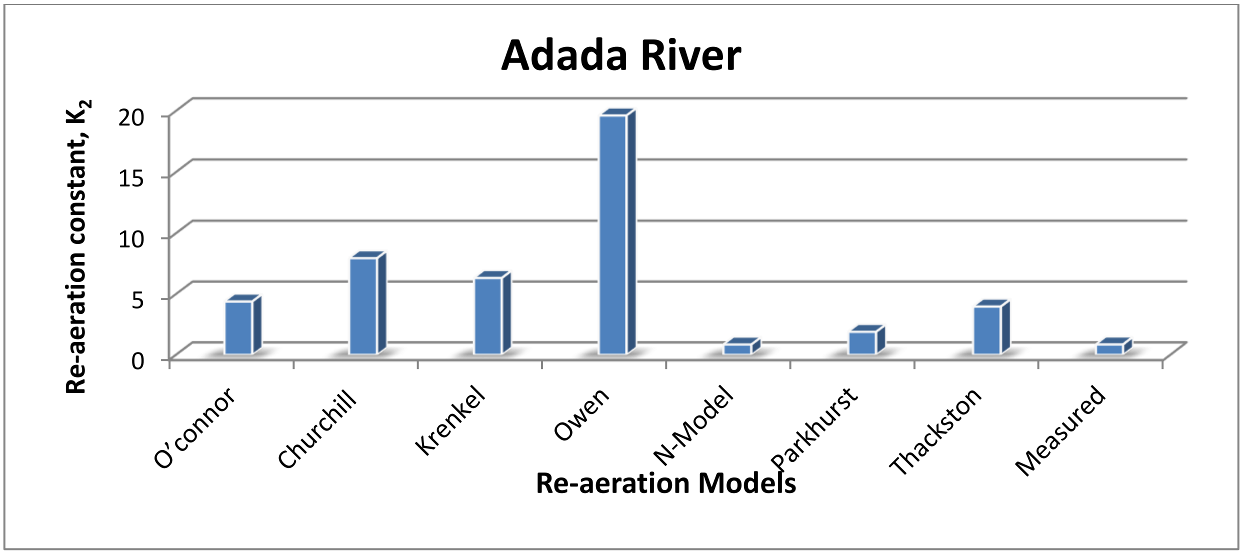


Fig 4.3: Variation of K_2 with Re-aeration models for Adada River

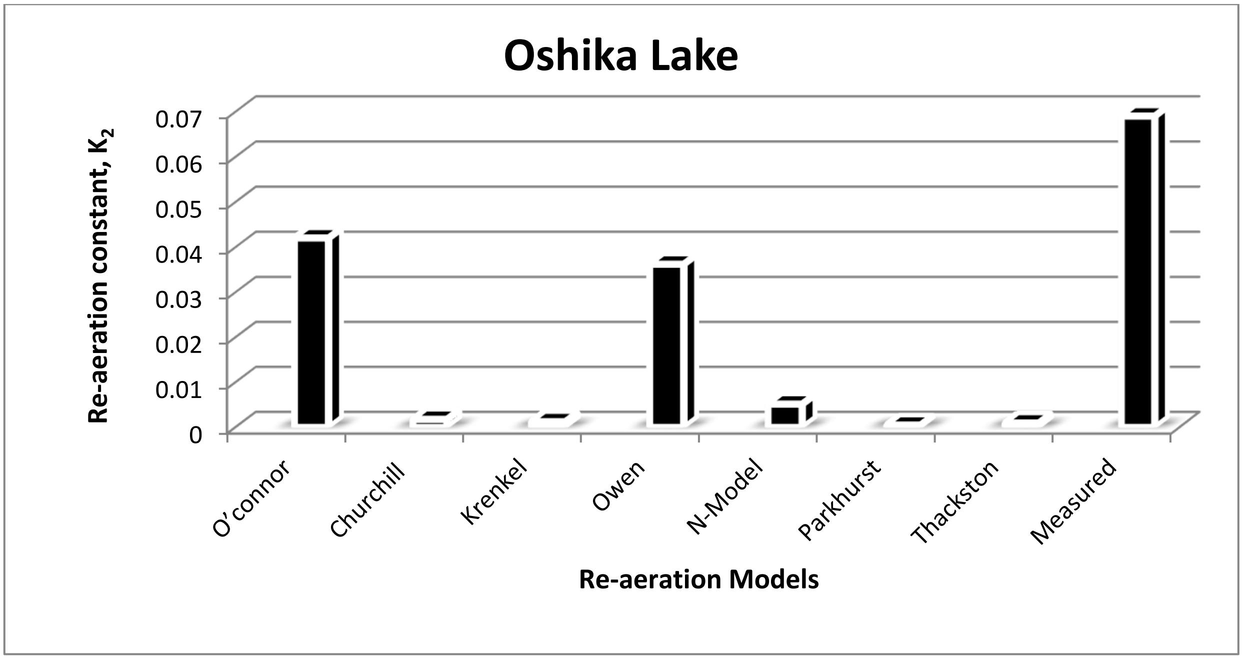


Fig 4.4: Variation of K_2 with Re-aeration models for Oshika Lake

The New Model (N-Model) was validated using the data obtained from Atuwara River as presented by Omole et al., (2013). The data sets are presented in Table 9 and 10 of the appendices.

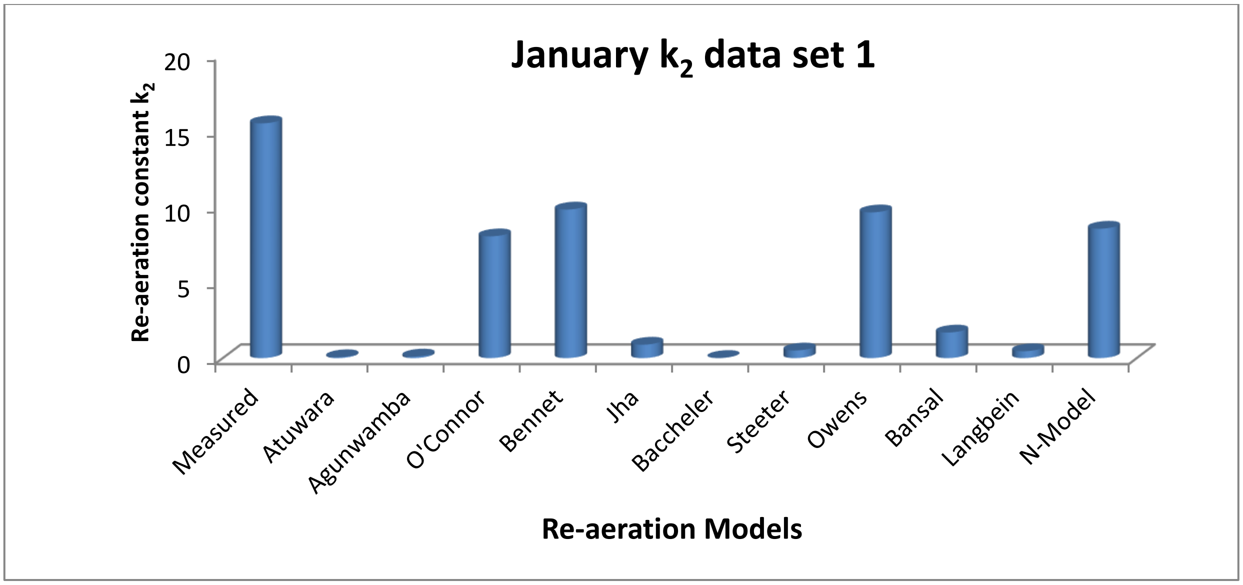


Fig 4.5: Simulated K_2 using various Re-aeration models for January data set 1 of Atuwara River

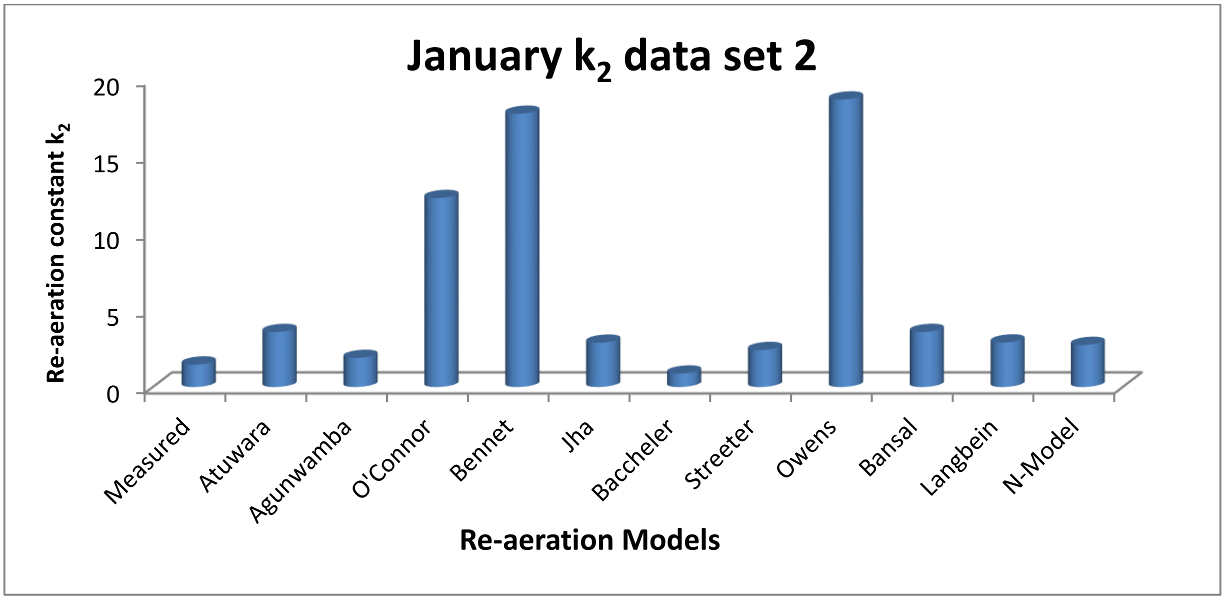


Fig 4.6: Simulated K_2 using various Re-aeration models for January data set 2 of Atuwara River

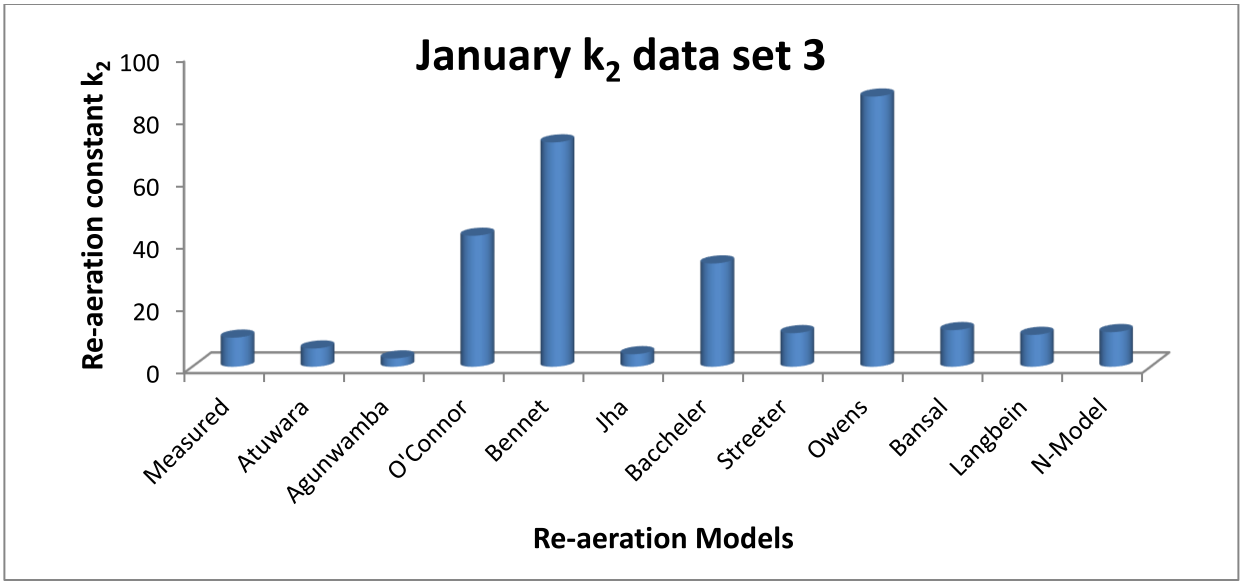


Fig 4.7: Simulated K_2 using various Re-aeration models for January data set 3 of Atuwara River

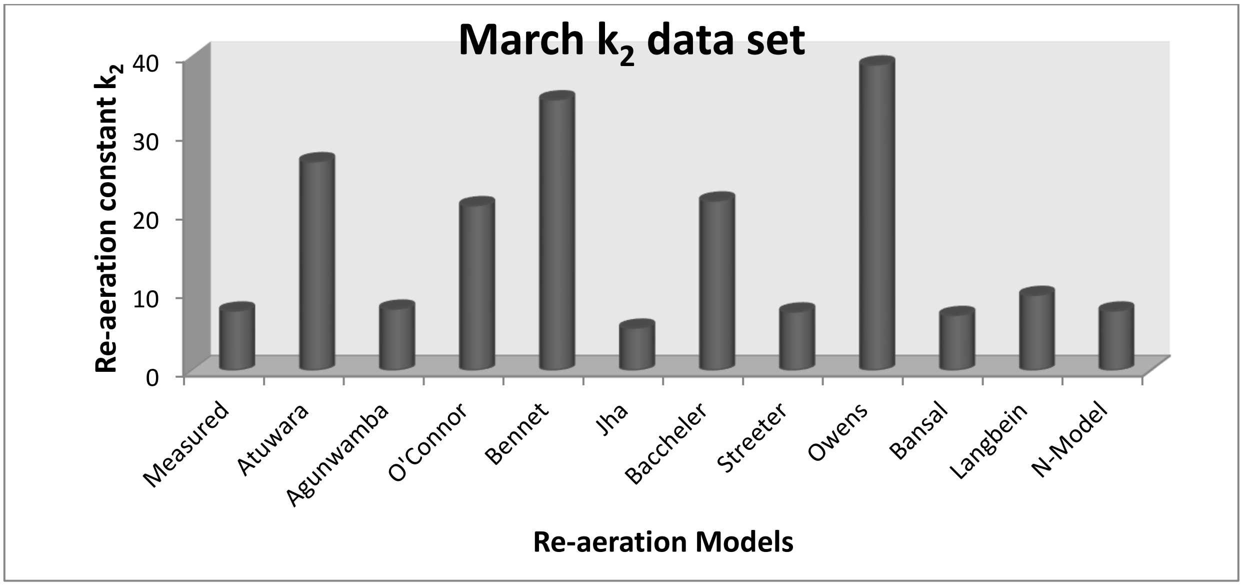


Fig 4.8: Simulated K_2 using various Re-aeration models for March data set of Atuwara River

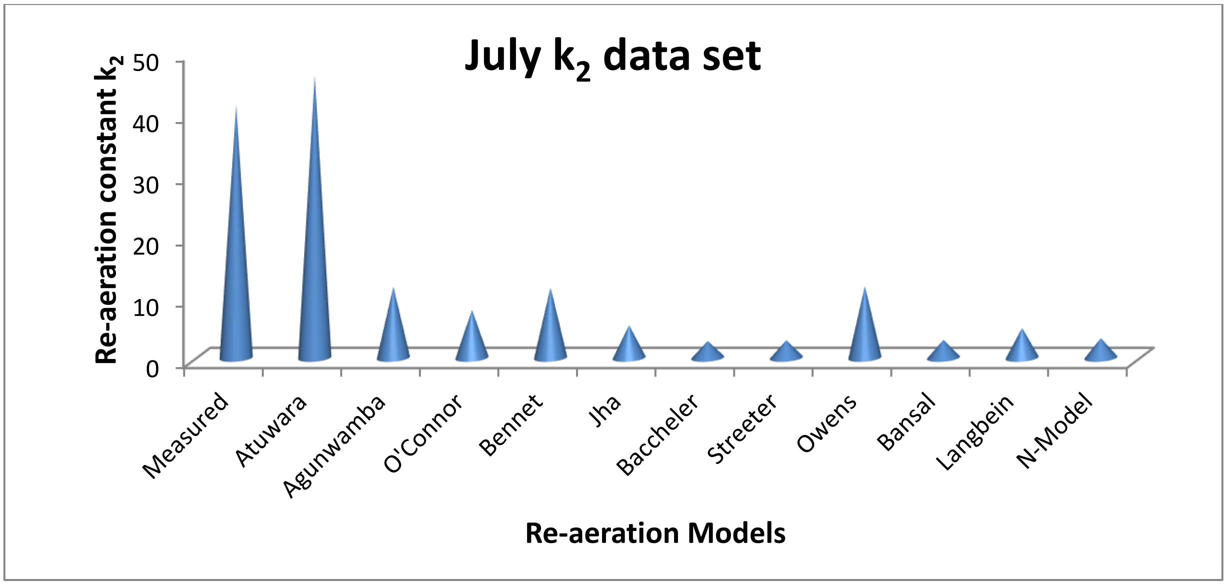


Fig 4.9: Simulated K_2 using various Re-aeration models for July data set of Atuwara River

4.2 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. 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 which the phytoplankton used 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.

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 Otammiri

River was 0.075 as shown in (Figure 4.1) 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.

The re-aeration coefficient for River Kaduna was 0.8481. N-Model predicted an accurate value of 0.848, (Figure 4.2), producing a 99.8% correlation coefficient while Parkhurst model gave a result of 0.954 which can be concluded was in near agreement to the reported re-aeration coefficient with 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.

The re-aeration coefficient for Adada River gave a mean value of 0.85, (Figure 4.3) above. N-Model predicted a value of 0.845, an accuracy of 99.8% correlation coefficient while Parkhurst produced a value of 1.888 which is in nearest 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.

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 4.4, amounting to 57.8% correlation value and Owen gave 0.0362 producing 51.4% correlation which we can consider to be a little reasonable unlike the others; Thackston, Parkhurst, Churchill, Krenkel and 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 equation. However, the accuracy of these models cannot be guaranteed when used to predict the re-aeration coefficient of rivers theoretically without having to go through some phase of laboratory testing. Notwithstanding, these models could offer some reasonable idea about the re-aeration rate of rivers in consideration. Though some of these models are theoretical, others were empirically generated. The reason behind the performance of these other models could come from the fact that some of these models were developed by using re-analyses of multiple existing data.

Attempt was made to validate the N-Model using the Atuwara river data sets and the following analyses were carried-out:

For the January data set 1, Figure 4.5 shows that Bennet, O'Connor, N-Model and Owens' models were relatively close but did not pass the confidence limit ($wi \geq 0.047$), though a positive PBIAS value was had. Further model evaluation demonstrated that Baccheler, Agunwamba and Atuwara had a negative PBIAS value which it disqualified . Figure 4.6 shows however that, Agunwamba model had RSR value of 0.79 which was better than N-Model with RSR of 0.92. Therefore, the preferred model for this data set is Agunwamba model. Langbein, Streeter and Jha models pass the confidence limit also with an acceptable NSE value range. In Figure 4.7, Bansal, Langbein, N-Model and Streeter models pass the confidence limit.

However, Langbein model was better with the lowest RSR value of 0.74. PBIAS results disqualified Owens, Bennet, O'Connor and Baccheler's models due to their negative values.

For the randomly selected March data set as shown in Figure 4.8, only Agunwamba, Streeter, N-Model, Bansal, and Langbein models with w_i = 0.81, 0.82, 0.78, 0.72 and 0.68, respectively, passed the confidence limit. PBIAS results disqualified Owens, Bennet, O'Connor, Baccheler and Atuwara models because of their negative values. Both NSE and RSR values were acceptable for the models even though Streeter model recorded lower RSR and a better NSE result. Therefore, Streeter model is the preferred model for the randomly selected March data set.

The randomly selected July data set was the only rainy season data set used in the study. The rainy season is characterized by high discharge and dilution. The model that passed the confidence limit (wi ≥ 0.047) was Atuwara with w_i = 0.57. PBIAS values for the other models were negative, thus disqualifying them. The only model with a positive PBIAS value was Atuwara model. The NSE value for the model was within the acceptable range with an RSR value of 0.84.

Based on the analyses above, it can be seen that the N-Model was relatively fair in the simulation of re-aeration results of Atuwara river, although there were instances of complete failure.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 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. There was a variation in the re-aeration coefficient of Otammiri river from $0.0000362-0.078$; river Kaduna (0.141−4.32); $1.888-19.621$ for Adada river and Oshika lake (0.000144−0.042). From this research work, N-Model re-aeration model which was derived from O'connor Model is conveniently adopted. In it, the re-aeration coefficient is directly proportional to stream velocity and inversely proportional to the water depth. The values for the re-aeration coefficients as obtained is significantly low, implying that these rivers are polluted to a great degree and as such, is unsafe as potable water without treatment for human consumption.

In comparing the result with the already existing models, statistical measures were employed. The aim of model evaluation is to check the level of agreement between the measured and stimulated data. From the findings, the measure data shows that river Adada has the highest value of re-aeration coefficient (K_2) (0.85) while Oshika lake has the lowest value of re-aeration coefficient (K_2) with 0.069.

The standard error values for the re-aeration models ranged from 4%−2208.35%. The reason for this enormous error in calculating k_2 with these models was due to the fact that the prevailing stream conditions from which these models were formulated varies significantly from the rivers being considered here. This fact comes to bear with the result obtained from Oshika Lake when 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 streamflow characteristics from these rivers, hence, the high level of accuracy. The self purification capacity of these rivers is low.

5.2 Recommendations

Since there is no known model that can effectively and accurately predict the re-aeration rate of any river, the following observations is therefore recommended:

i. Empirical model should be developed to predict the re-aeration constant of rivers with similar stream conditions which include the nature of the stream, location, type of effluent discharged and geometric properties of the stream.

ii. O'connor and Dobbins equation should be adopted as bases for the formulation of such models.

iii. A brief sample analysis of such rivers should be conducted if not already in existence, in order to obtain a reliable data source for the empirical derivation and/or calibration of such models.

iv. For reliability, the models should be re-calibrated from time to time due to the varying environmental conditions and the prevailing activities around the stream location.

v. N-Model is highly recommended for the prediction of re-aeration rate of Otammiri, Adada and Kaduna River as well as rivers within these regions and/or with similar stream flow characteristics.

5.3 Contribution to Knowledge

The following contributions were made to the pool of already existing ones in this subject of re-aeration study of rivers;

i. **Innovative Sanitation Solutions**: By designing suspended septic tanks tailored to the unique hydrological conditions of the Niger Delta, this project advances the field of sustainable sanitation technology. The innovative approach of elevating septic systems minimizes the risk of contamination from flooding, a prevalent issue in the region. This research highlights the importance of context-specific solutions that address local environmental challenges while promoting health and sanitation.

ii. **Impact on Water Quality**: The study elucidates the relationship between improved sanitation infrastructure and water quality in riverine environments. By implementing suspended septic tanks, this project aims to reduce the incidence of open defecation, thereby decreasing pathogen loads in surrounding water bodies. The research contributes to understanding how effective sanitation solutions can lead to improved dissolved oxygen levels and overall aquatic ecosystem health.

iii. **Public Health Implications**: The findings of this project emphasize the critical link between sanitation, water quality, and public health. By addressing the challenges of open defecation and inadequate waste management, this research seeks to mitigate the prevalence of waterborne diseases, enhancing community health outcomes. This aspect is particularly significant in regions like the Niger Delta, where health issues stemming from poor sanitation are widespread.

iv. **Community Engagement and Participation**: The project underscores the necessity of involving local communities in the planning and implementation of sanitation solutions.

Through participatory approaches, the research emphasizes that successful interventions must align with cultural practices and community needs. This insight contributes to the literature on community-driven development and highlights the importance of stakeholder involvement in environmental health initiatives.

v. **Framework for Future Research**: By identifying gaps in current sanitation practices and proposing an empirical framework for evaluating the effectiveness of suspended septic tanks, this project paves the way for future research in similar contexts. It provides a model for assessing the socio-environmental impacts of sanitation interventions and invites further exploration into the scalability and adaptability of such systems in other vulnerable regions.

vi. **Policy Recommendations**: The project offers valuable insights for policymakers and practitioners in the field of water and sanitation. It emphasizes the need for integrated policies that address both sanitation infrastructure and water quality management. The research findings can inform regulatory frameworks, guiding investments in sanitation technologies that are sustainable and resilient to climate change.

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APPENDICES

Computation of Re-aeration Constants Using Some Selected Models for Each River

APPENDIX 1: Data obtained from Otammiri field work.

Station	Distance	Depth, d(m)	Width, w(m)	Velocity, V (m/s)	Area A=wd(m^2)	Flow rate Q=AV(m^3/s)
1	0	0.85	9.1	0.018	7.735	0.139
2	100	1.95	18.1	0.016	35.295	0.565
3	200	1.66	22.1	0.017	36.686	0.624
4	300	2.25	36.0	0.016	81.000	1.296
5	400	4.70	72.0	0.015	338.400	5.076
6	500	8.65	135.0	0.014	1167.750	16.349
7	600	4.45	153.0	0.015	680.850	10.213
Average		3.501	-	0.016	-	-

Source: Uchenna and Nwaogazie (2011)

APPENDIX 2: Hydraulic data for river kaduna for the month of February, 2014

Sampling points	Mean velocity (m/s)	Hydraulic radius (m)	Mean depth (m)	Volumetric flow rate(m^3/s)
S1	0.1800	0.8133	1.6266	60.6
S2	0.1413	0.9150	1.8300	64.1
S3	0.1533	0.9583	1.9166	82.87
S4	0.2566	0.6500	1.3000	0.71
S5	0.1386	0.3700	0.7400	9.63
S6	0.2333	0.5533	1.1066	3.6
S7	0.2033	0.4283	0.8566	45.6
S8	0.2733	0.6150	1.2300	97.5

Average mean velocity, depth and discharge for the month of February, 2014 were found to be respectively 0.1975m/s, 1.33m and 61.1m^3/s.

Source: Ogbozige and others (2017)

APPENDIX 3: R-squared values of six (6) models when tested with experimentally generated River Kaduna data.

Months	k_2 River Kaduna	k_2 Agunwamba *et al.*,	k_2 Omole *et al.*,	k_2 Streeter &Phelps	k_2 Garg *et al.*,	k_2 Jha *et al.*,	k_2 Bach & Lee
February	0.8481	0.5482	0.5569	0.7444	0.6627	0.6978	0.8036
March	0.5142	0.5636	0.5402	0.9507	0.7834	0.2698	0.3319
April	0.8748	0.9118	0.9120	0.6777	0.5301	0.9303	0.9299
May	0.5150	0.8626	0.8709	0.3406	0.1798	0.8045	0.491
June	0.3956	0.7291	0.7286	0.4161	0.4085	0.6632	0.4430
July	0.6552	0.6202	0.6247	0.6759	0.6854	0.6772	0.6468

Source: Ogbozige and others (2017)

APPENDIX 4: Summary of Geomorphological Parameters of Otammiri River

Parameter		**Reach 1**	**Reach 2**	**Reach 3**
Channel plan view		Single threaded	Multi threaded	Single threaded
Average water surface slope(S) m/m		0.000109671	8.45557E-05	0.000306698
Stream or channel length (SL) m		21,097.14	24,032.93	4,650.63
Stream or channel slope		0.00038	0.00051	0.00157
Valley length (VL) m	**Left Bank**	20,898.43	24,708.42	4,561.13
	Right Bank	21,097.14	22,483.18	4,802.10
Valley slope (VS) m/m	**Left Bank**	0.000306281	0.00064	0.00140
	Right Bank	0.000375634	0.000515	0.001142501
Sinuosity (VS/SL)		0.907686209	1.13997	0.809256879
Sinuosity (SL/VL)		1.004731857	1.018525	0.993382274
Entrenchment ratio (W_{fpa}/ W_{bfl})		2.057847328	1.795573	1.936598257
Width/ Depth ratio		103.074	221.600	142.171
Stream Power (N/m/s)		2.41	1.49	2.67

Source: Uchenna D. M and Nwaogazie I. L (2011)

APPENDIX 5: Raw results obtained in the site during the course of sampling of Adada River

S/NO	$D1-DO$ (mg/l)	$D2-DO$ (mg/l)	$DO1_{s(\frac{mg}{l})}$	$DO2_{s(\frac{mg}{l})}$	V(m/s)	W(m)	D(m)
1	5.2	5.4	7.9	7.8	0.221	7.2	0.9
2	4.8	5.2	7.8	7.9	0.098	10.3	1.24
3	5.0	5.4	7.7	7.8	0.125	8.5	1.21
4	5.3	5.6	7.9	7.9	0.251	9.1	0.95
5	5.4	5.7	7.9	7.9	0.321	4.7	0.62
6	5.5	5.8	7.8	7.8	0.521	3.5	0.83
7	5.8	6.3	7.9	7.8	0.753	4.06	0.42
8	5.6	5.9	7.9	7.8	0.556	7.25	0.33
9	5.7	6.1	7.8	7.8	0.615	2.04	0.55
10	5.7	6.2	7.9	7.9	0.623	4.4	0.53

Source: Nwidi ignatius chineke (2010).

APPENDIX 6: Temperature and wind speed for Adada River for September and October,2009 obtained from the department of Crop science University of Nsukka, Nigeria.

	SEPTEMBER		OCTOBER	
DAY	Temp(°C)	Wind speed (km/h)	Temp(°C)	Wind speed (km/h)
1	28	65.41	29	77.40
2	28	43.31	27	92.32
3	29	63.78	29	63.58
4	28	98.26	32	74.12
5	27	47.70	32	77.07
6	29	105.48	28	63.58
7	30	115.49	28	66.90
8	27	44.90	27	90.12
9	30	91.99	27	112.03
10	28	73.37	27	90.12
11	29	99.06	29	112.03
12	26	45.54	26	39.88
13	28	64.13	29	56.37
14	29	121.11	27	54.66
15	27	73.53	29	101.49
16	28	53.56	27	81.55
17	29	49.53	29	55.27
18	26	16.78	31	44.97
19	27	42.72	24	82.33
20	26	69.57	29	81.76
21	27	74.87	29	75.43
22	29	73.47	29	74.63
23	28	86.03	27	62.25
24	30	53.98	27	57.78
25	30	75.01	28	81.16
26	29	67.02	30	62.09
27	27	77.04	27	79.41
28	30	65.10	29	85.51
29	29	92.32	28	66.08
30	28	104.79	30	78.09
31			30	74.52

Source: Nwidi ignatius chineke (2010).

APPENDIX 7: Mean monthly Analytical data of Oshika lake/stream

s/n	Parameter	Method	Eshia Seas on average	Mean monthly sampled data of stations											
				1	2	3	4	5	6	7	8	9	10	11	12
1	Time	Stop watch		30	30	30	30	30	30	30	30	30	30	30	30
2	Ph	API-RP 45	5.90-6.40	5.5	5.7	5.7	5.6	5.4	5.3	5.2	5.3	5.3	5.2	5.2	5.3
3	Temp, ℃	API-RP 45	27.0-29.1	28	28	29	28	28	29	29	27	27	28	27	27
4	Turbidity, NTU	APHA 2130	5.4-44.9	7.85	0.23	1.45	20.1	3.46	12.04	4.92	5.73	5.31	7.42	5.58	5.31
5	Salinity (%)	ASTM D512	7.2-98.5	0.65	0.92	1.11	1.21	1.91	1.07	0.94	0.84	0.77	0.67	0.47	0.04
6	DO(mg/l)	Meter	5.20-6.50	3.8	3.64	2.61	2.17	2.19	2.49	2.85	3.09	3.34	3.60	3.97	4.43
7	BOD (mg/l)	ALPHA 5210-B	0.9-1.80	3.0	12.94	16.28	15.81	15.42	14.49	13.63	13.00	12.39	11.95	11.45	10.67
8	COD (mg/l)	ALPHA 508	10.8-18.5	8.05	6.25	6.10	7.1	29.66	23.33	23.33	29.70	32.55	8.05	34.4	16.33
9	Oil and grease	ASTM D3921	0.9-31.20	0.018	0.460	0.602	0.645	0.58	0.494	0.442	0.421	0.323	0.213	0.196	0.141
10	TSS(mg/l)	ASTM D1868	0.9-4.80	22.18	11.87	11.82	22.35	14.55	15.10	17.02	18.99	15.13	17.19	14.9	18.19
11	TDS(mg/l)	ASTM D1868	30.5-113.2	49.23	36.47	38.94	45.9	53.86	66.63	68.61	57.02	67.41	69.45	54.69	138.54
12	Conductivity (us/cm)	Meter	47.1-161.6	16.9	13.76	19.0	23.7	29.1	27.31	29.31	40.65	40.77	35.30	38.99	35.76
13	Velocity (m^2/s)		NS	0.00105	0	0	0	0.01	0.001	0.01	0.03	0.015	0.017	0.013	0.01
14	Depth(m)		NS	2.3	2.5	2.3	2.5	2.7	2.7	3.0	3.5	3.5	4.0	3.75	3.2
15	Width(m)		NS	20.55	18	15	15	20	20	25	30	35	45	38	30
16	Flow rate (m^3/s)		NS	0.050	0	0	0	0.01	0.02	0.05	0.05	0.07	0.15	0.13	0.01

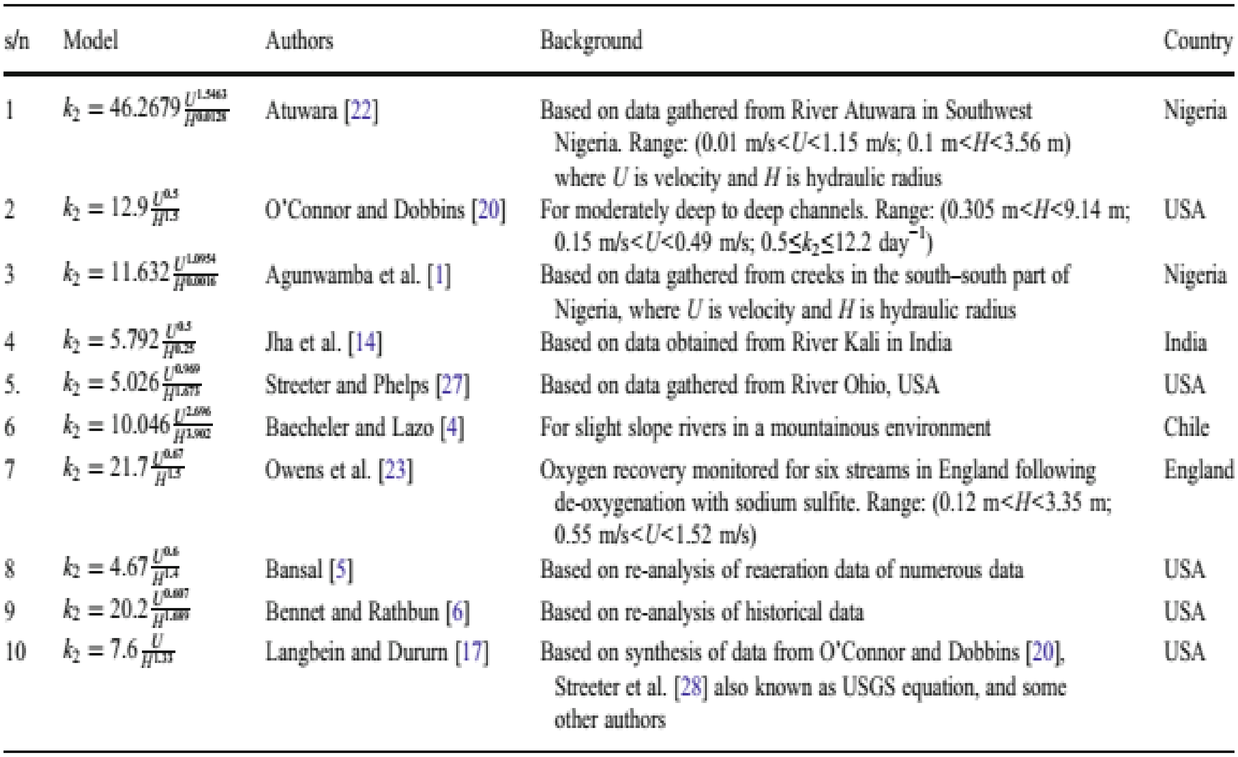
Source: Ugbebor and others (2012)

APPENDIX 8: k_2 from oshika lake field data (dry season)

Distance	Nov	Dec	Jan	Feb	Mar	Apr	Mean K_2
200	0.327	0.145	0.221	0.250	0.154	0.049	0.191
400	0.217	0.127	0.150	0.134	0.134	0.091	0.142
600	0.170	0.103	0.122	0.102	0.094	0.057	0.108
800	0.146	0.090	0.084	0.094	0.069	0.042	0.087
1000	0.121	0.058	0.062	0.066	0.054	0.031	0.065
1200	0.091	0.040	0.047	0.047	0.045	0.017	0.048
1400	0.074	0.029	0.039	0.037	0.035	0.014	0.038
1600	0.057	0.020	0.033	0.031	0.026	0.012	0.030
1800	0.043	0.014	0.028	0.024	0.025	0.008	0.024
2000	0.034	0.010	0.021	0.019	0.012	0.007	0.017
2200	0.022	0.003	0.015	0.011	0.007	0.004	0.010
2400	0.007	0.002	0.004	0.002	0.001	0.002	0.003
Mean K_2 Per Month	0.109	0.053	0.069	0.068	0.055	0.028	

Source: Ugbebor and others (2012)

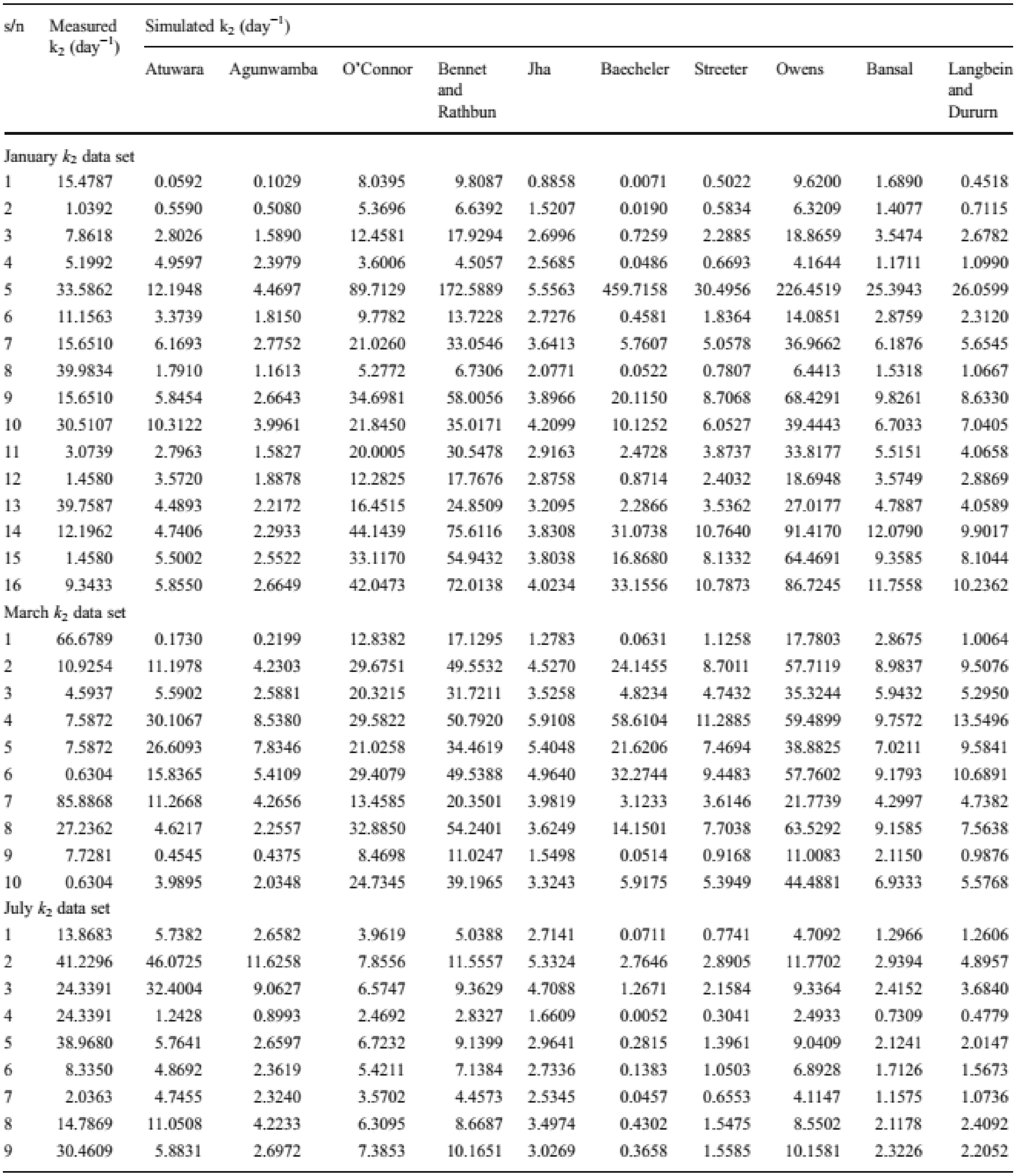
Table 9: Short-listed models for information criteria test



s/n	Model	Authors	Background	Country
1	$k_2 = 46.2679\frac{U^{1.5463}}{H^{0.0128}}$	Atuwara [22]	Based on data gathered from River Atuwara in Southwest Nigeria. Range: (0.01 m/s<U<1.15 m/s; 0.1 m<H<3.56 m) where U is velocity and H is hydraulic radius	Nigeria
2	$k_2 = 12.9\frac{U^{0.5}}{H^{1.5}}$	O'Connor and Dobbins [20]	For moderately deep to deep channels. Range: (0.305 m<H<9.14 m; 0.15 m/s<U<0.49 m/s; $0.5 \leq k_2 \leq 12.2$ day^{-1})	USA
3	$k_2 = 11.632\frac{U^{1.0954}}{H^{0.0016}}$	Agunwamba et al. [1]	Based on data gathered from creeks in the south–south part of Nigeria, where U is velocity and H is hydraulic radius	Nigeria
4	$k_2 = 5.792\frac{U^{0.5}}{H^{0.25}}$	Jha et al. [14]	Based on data obtained from River Kali in India	India
5.	$k_2 = 5.026\frac{U^{0.969}}{H^{1.673}}$	Streeter and Phelps [27]	Based on data gathered from River Ohio, USA	USA
6	$k_2 = 10.046\frac{U^{2.696}}{H^{3.902}}$	Baecheler and Lazo [4]	For slight slope rivers in a mountainous environment	Chile
7	$k_2 = 21.7\frac{U^{0.67}}{H^{1.85}}$	Owens et al. [23]	Oxygen recovery monitored for six streams in England following de-oxygenation with sodium sulfite. Range: (0.12 m<H<3.35 m; 0.55 m/s<U<1.52 m/s)	England
8	$k_2 = 4.67\frac{U^{0.6}}{H^{1.4}}$	Bansal [5]	Based on re-analysis of reaeration data of numerous data	USA
9	$k_2 = 20.2\frac{U^{0.607}}{H^{1.689}}$	Bennet and Rathbun [6]	Based on re-analysis of historical data	USA
10	$k_2 = 7.6\frac{U}{H^{1.33}}$	Langbein and Durum [17]	Based on synthesis of data from O'Connor and Dobbins [20], Streeter et al. [28] also known as USGS equation, and some other authors	USA

Source: Omole *et al*., (2013)

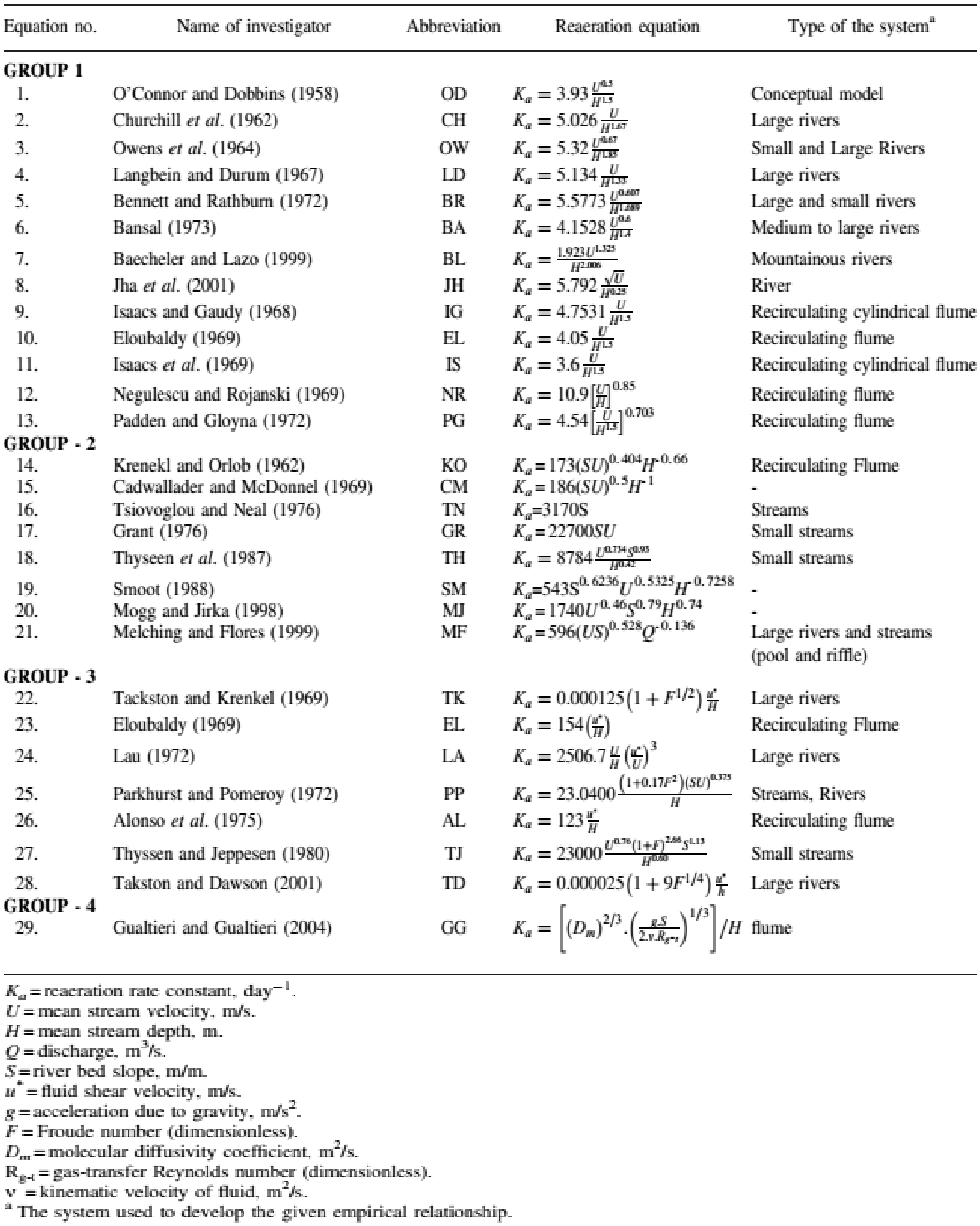
Table 10: January k_2 data set, March k_2 data set, and July k_2 data set



s/n	Measured k_2 (day^{-1})	Simulated k_2 (day^{-1})									
		Atuwara	Agunwamba	O'Connor	Bennet and Rathbun	Jha	Baecheler	Streeter	Owens	Bansal	Langbein and Durum
January k_2 data set											
1	15.4787	0.0592	0.1029	8.0395	9.8087	0.8858	0.0071	0.5022	9.6200	1.6890	0.4518
2	1.0392	0.5590	0.5080	5.3696	6.6392	1.5207	0.0190	0.5834	6.3209	1.4077	0.7115
3	7.8618	2.8026	1.5890	12.4581	17.9294	2.6996	0.7259	2.2885	18.8659	3.5474	2.6782
4	5.1992	4.9597	2.3979	3.6006	4.5057	2.5685	0.0486	0.6693	4.1644	1.1711	1.0990
5	33.5862	12.1948	4.4697	89.7129	172.5889	5.5563	459.7158	30.4956	226.4519	25.3943	26.0599
6	11.1563	3.3739	1.8150	9.7782	13.7228	2.7276	0.4581	1.8364	14.0851	2.8759	2.3120
7	15.6510	6.1693	2.7752	21.0260	33.0546	3.6413	5.7607	5.0578	36.9662	6.1876	5.6545
8	39.9834	1.7910	1.1613	5.2772	6.7306	2.0771	0.0522	0.7807	6.4413	1.5318	1.0667
9	15.6510	5.8454	2.6643	34.6981	58.0056	3.8966	20.1150	8.7068	68.4291	9.8261	8.6330
10	30.5107	10.3122	3.9961	21.8450	35.0171	4.2099	10.1252	6.0527	39.4443	6.7033	7.0405
11	3.0739	2.7963	1.5827	20.0005	30.5478	2.9163	2.4728	3.8737	33.8177	5.5151	4.0658
12	1.4580	3.5720	1.8878	12.2825	17.7676	2.8758	0.8714	2.4032	18.6948	3.5749	2.8869
13	39.7587	4.4893	2.2172	16.4515	24.8509	3.2095	2.2866	3.5362	27.0177	4.7887	4.0589
14	12.1962	4.7406	2.2933	44.1439	75.6116	3.8308	31.0738	10.7640	91.4170	12.0790	9.9017
15	1.4580	5.5002	2.5522	33.1170	54.9432	3.8038	16.8680	8.1332	64.4691	9.3585	8.1044
16	9.3433	5.8550	2.6649	42.0473	72.0138	4.0234	33.1556	10.7873	86.7245	11.7558	10.2362
March k_2 data set											
1	66.6789	0.1730	0.2199	12.8382	17.1295	1.2783	0.0631	1.1258	17.7803	2.8675	1.0064
2	10.9254	11.1978	4.2303	29.6751	49.5532	4.5270	24.1455	8.7011	57.7119	8.9837	9.5076
3	4.5937	5.5902	2.5881	20.3215	31.7211	3.5258	4.8234	4.7432	35.3244	5.9432	5.2950
4	7.5872	30.1067	8.5380	29.5822	50.7920	5.9108	58.6104	11.2885	59.4899	9.7572	13.5496
5	7.5872	26.6093	7.8346	21.0258	34.4619	5.4048	21.6206	7.4694	38.8825	7.0211	9.5841
6	0.6304	15.8365	5.4109	29.4079	49.5388	4.9640	32.2744	9.4483	57.7602	9.1793	10.6891
7	85.8868	11.2668	4.2656	13.4585	20.3501	3.9819	3.1233	3.6146	21.7739	4.2997	4.7382
8	27.2362	4.6217	2.2557	32.8850	54.2401	3.6249	14.1501	7.7038	63.5292	9.1585	7.5638
9	7.7281	0.4545	0.4375	8.4698	11.0247	1.5498	0.0514	0.9168	11.0083	2.1150	0.9876
10	0.6304	3.9895	2.0348	24.7345	39.1965	3.3243	5.9175	5.3949	44.4881	6.9333	5.5768
July k_2 data set											
1	13.8683	5.7382	2.6582	3.9619	5.0388	2.7141	0.0711	0.7741	4.7092	1.2966	1.2606
2	41.2296	46.0725	11.6258	7.8556	11.5557	5.3324	2.7646	2.8905	11.7702	2.9394	4.8957
3	24.3391	32.4004	9.0627	6.5747	9.3629	4.7088	1.2671	2.1584	9.3364	2.4152	3.6840
4	24.3391	1.2428	0.8993	2.4692	2.8327	1.6609	0.0052	0.3041	2.4933	0.7309	0.4779
5	38.9680	5.7641	2.6597	6.7232	9.1399	2.9641	0.2815	1.3961	9.0409	2.1241	2.0147
6	8.3350	4.8692	2.3619	5.4211	7.1384	2.7336	0.1383	1.0503	6.8928	1.7126	1.5673
7	2.0363	4.7455	2.3240	3.5702	4.4573	2.5345	0.0457	0.6553	4.1147	1.1575	1.0736
8	14.7869	11.0508	4.2233	6.3095	8.6687	3.4974	0.4302	1.5475	8.5502	2.1178	2.4092
9	30.4609	5.8831	2.6972	7.3853	10.1651	3.0269	0.3658	1.5585	10.1581	2.3226	2.2052

Source: Omole *et al*. (2013)

Table 11: Re-aeration coefficients for rivers and streams



Equation no.	Name of investigator	Abbreviation	Reaeration equation	Type of the system[a]
GROUP 1				
1.	O'Connor and Dobbins (1958)	OD	$K_a = 3.93\frac{U^{0.5}}{H^{1.5}}$	Conceptual model
2.	Churchill *et al.* (1962)	CH	$K_a = 5.026\frac{U}{H^{1.67}}$	Large rivers
3.	Owens *et al.* (1964)	OW	$K_a = 5.32\frac{U^{0.67}}{H^{1.85}}$	Small and Large Rivers
4.	Langbein and Durum (1967)	LD	$K_a = 5.134\frac{U}{H^{1.33}}$	Large rivers
5.	Bennett and Rathburn (1972)	BR	$K_a = 5.5773\frac{U^{0.607}}{H^{1.689}}$	Large and small rivers
6.	Bansal (1973)	BA	$K_a = 4.1528\frac{U^{0.6}}{H^{1.4}}$	Medium to large rivers
7.	Baecheler and Lazo (1999)	BL	$K_a = \frac{1.923U^{1.323}}{H^{2.006}}$	Mountainous rivers
8.	Jha *et al.* (2001)	JH	$K_a = 5.792\frac{\sqrt{U}}{H^{0.25}}$	River
9.	Isaacs and Gaudy (1968)	IG	$K_a = 4.7531\frac{U}{H^{1.5}}$	Recirculating cylindrical flume
10.	Eloubaldy (1969)	EL	$K_a = 4.05\frac{U}{H^{1.5}}$	Recirculating flume
11.	Isaacs *et al.* (1969)	IS	$K_a = 3.6\frac{U}{H^{1.5}}$	Recirculating cylindrical flume
12.	Negulescu and Rojanski (1969)	NR	$K_a = 10.9\left[\frac{U}{H}\right]^{0.85}$	Recirculating flume
13.	Padden and Gloyna (1972)	PG	$K_a = 4.54\left[\frac{U}{H^{1.5}}\right]^{0.703}$	Recirculating flume
GROUP - 2				
14.	Krenekl and Orlob (1962)	KO	$K_a = 173(SU)^{0.404}H^{-0.66}$	Recirculating Flume
15.	Cadwallader and McDonnel (1969)	CM	$K_a = 186(SU)^{0.5}H^{-1}$	-
16.	Tsiovoglou and Neal (1976)	TN	$K_a = 3170S$	Streams
17.	Grant (1976)	GR	$K_a = 22700SU$	Small streams
18.	Thyseen *et al.* (1987)	TH	$K_a = 8784\frac{U^{0.734}S^{0.93}}{H^{0.42}}$	Small streams
19.	Smoot (1988)	SM	$K_a = 543S^{0.6236}U^{0.5325}H^{-0.7258}$	-
20.	Mogg and Jirka (1998)	MJ	$K_a = 1740U^{0.46}S^{0.79}H^{0.74}$	-
21.	Melching and Flores (1999)	MF	$K_a = 596(US)^{0.528}Q^{-0.136}$	Large rivers and streams (pool and riffle)
GROUP - 3				
22.	Tackston and Krenkel (1969)	TK	$K_a = 0.000125\left(1 + F^{1/2}\right)\frac{u^*}{H}$	Large rivers
23.	Eloubaldy (1969)	EL	$K_a = 154\left(\frac{u^*}{H}\right)$	Recirculating Flume
24.	Lau (1972)	LA	$K_a = 2506.7\frac{U}{H}\left(\frac{u^*}{U}\right)^3$	Large rivers
25.	Parkhurst and Pomeroy (1972)	PP	$K_a = 23.0400\frac{\left(1+0.17F^2\right)(SU)^{0.375}}{H}$	Streams, Rivers
26.	Alonso *et al.* (1975)	AL	$K_a = 123\frac{u^*}{H}$	Recirculating flume
27.	Thyssen and Jeppesen (1980)	TJ	$K_a = 23000\frac{U^{0.76}(1+F)^{2.66}S^{1.13}}{H^{0.60}}$	Small streams
28.	Takston and Dawson (2001)	TD	$K_a = 0.000025\left(1 + 9F^{1/4}\right)\frac{u^*}{h}$	Large rivers
GROUP - 4				
29.	Gualtieri and Gualtieri (2004)	GG	$K_a = \left[(D_m)^{2/3}.\left(\frac{g.S}{2.v.R_{g-t}}\right)^{1/3}\right]/H$	flume

K_a = reaeration rate constant, day^{-1}.
U = mean stream velocity, m/s.
H = mean stream depth, m.
Q = discharge, m^3/s.
S = river bed slope, m/m.
u^* = fluid shear velocity, m/s.
g = acceleration due to gravity, m/s^2.
F = Froude number (dimensionless).
D_m = molecular diffusivity coefficient, m^2/s.
R_{g-t} = gas-transfer Reynolds number (dimensionless).
v = kinematic velocity of fluid, m^2/s.
[a] The system used to develop the given empirical relationship.

Source: Haider (2010)