Nigerian Journal of Technology (NIJOTECH)
Vol. 44, No. 3, September, 2025, pp.484 - 496
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://doi.org/10.4314/njt.v44i3.12

INTERLINKING STREAM MORPHOLOGY, WATER QUALITY, AND RE-AERATION RATES: A SEMI-EMPIRICAL MODELING STUDY OF EKULU STREAM, NIGERIA

AUTHORS:
C. C. Nnaji[1,*] and A. Ajah[2]

AFFILIATIONS:
[1,2]Department of Civil Engineering, University of Nigeria Nsukka, Enugu, Nigeria
[1]Faculty of Engineering and the Built Environment, University of Johannesburg, Johannesburg, South Africa

***CORRESPONDING AUTHOR:**
Email: chidozie.nnaji@unn.edu.ng

ARTICLE HISTORY:
Received: April 24, 2025.
Revised: July 30, 2025.
Accepted: August 11, 2025.
Published: October 15, 2025.

KEYWORDS:
Stream, Pollution, Re-aeration, Dissolved oxygen, Self-purification, Flow.

ARTICLE INCLUDES:
Peer review

DATA AVAILABILITY:
On request from author(s)

EDITORS:
Ozoemena Anthony Ani

FUNDING:
None

Abstract
*Global population explosions coupled with increase in industrial activities have resulted in a corresponding rise in effluent discharge which end up in streams and rivers. Re-aeration rate plays a vital role in the self-purification of these rivers and streams. This study was aimed at investigating the re-aeration of Ekulu Stream in Enugu metropolis and the effects of hydraulic factors and water quality parameters on its re-aeration coefficient (k_2). Water and sediment samples were obtained from a 2.56 km stretch of the Stream and subjected to physico-chemical characterization. Water samples were tested for temperature, pH, total dissolved solids, total solids, electrical conductivity, dissolved oxygen and biochemical oxygen demand. Hydraulic parameters of the channel namely, slope, velocity, flow depth and width were also measured and then used to estimate the value of k_2 at each sampling point based on ten selected empirical re-aeration models designated as E1 to E10. Dissolved oxygen values ranged from 2.4 to 5.4 mg/L indicating pronounced oxygen sag. The re-aeration coefficient of Ekulu Stream as computed using the various models ranged from 1.42 to 57.11 day^{-1}. The models of Churchill (E4), Owens et al (E8 & E9) and Bennett and Rathbun (E1 & E2) gave the highest k_2 values ranging 57.11 to 18.90, 49.46 to 16.56, 47.95 to 15.40, 45.96 to 23.56 and 41.54 to 14.74 day^{-1} respectively. Apart from E1 and E3, all the models used in this study produced k_2 values that have positive relationship with pH of water. Between 55 and 91% of the variation in the value of K_2 can be explained by a linear combination of TDS and the interaction of electrical conductivity and temperature (EC*Temp). Re-aeration models incorporating only velocity and flow depth (E2, E4, E7, E8 & E9) exhibited the best linear relationship with water quality parameters with p-values of 0.012, 0.001, 0.000, 0.005 and 0.014 and R^2 values of 0.72, 0.88, 0.9, 0.78 and 0.71 respectively. Water quality parameters affect the re-aeration rates of Ekulu Stream. This finding will open a new research frontier with respect to stream re-aeration and is expected to help improve re-aeration models by integrating water quality parameters or an index thereof.*

1.0 INTRODUCTION
Streams and rivers play a crucial role in meeting domestic water demands of rural and semi-urban dwellers who do not have access to municipal water supply. Aside from the necessity of water for drinking, water resources are essential to many economic sectors, including agriculture, livestock production, forestry, industrial activities, the production of hydropower, fishing, and other creative

HOW TO CITE:
Nnaji, C. C., and Ajah, A. "Interlinking Stream Morphology, Water Quality, and Re-Aeration Rates: A Semi-Empirical Modeling Study of Ekulu Stream, Nigeria", *Nigerian Journal of Technology*, 2025; 44(3), pp. 484 – 496; https://doi.org/10.4314/njt.v44i3.12

endeavors. Besides, many municipal water supply schemes draw raw water from nearby streams and rivers which is then subjected to purification before storage and distribution. The cost of water treatment is directly proportional to the quality of raw water and the types of contaminants present [1], [2]. Unfortunately, many of these urban streams have suffered rapid water quality deterioration as a result of unregulated use and uncontrolled discharge of effluent, solid waste dumping and inflow of heavily polluted runoff from the surrounding catchment [3].

In developing countries where wastewater and stormwater treatment facilities are not given priority, urban streams become the ultimate recipient and confluence point of a consortium of effluent from domestic, industrial and commercial sources. Fecal matter and associated pathogens from open defecation and open sewage channels readily make their way into adjoining streams [4]. Application of animal manure to farmlands and effluent from wastewater treatment plants have been implicated for nutrient overload in surface waters [5]. Organic and inorganic substances in pesticides, herbicides and fertilizers are leached from farmlands and gardens into streams, rivers and lakes. Once these pollutants enter the stream, they are transported downstream through the entire river network [6]. Streams which served as community drinking water sources have been rendered unfit by contaminants from multifarious point and diffuse sources of pollution. Several unregulated activities with persistent adverse environmental impact, particularly livestock farming are preferentially situated along stream banks for ease of water supply and wastewater discharge without any form of treatment.

The situation has been further exacerbated by non-enforcement/non-compliance of environmental laws and regulations as well as the prioritization of revenue collection over environmental sustainability by relevant government agencies [7]. The cost of water treatment for municipal supply has increasingly assumed an upward trajectory because of increased chemical and technology requirements to remove emerging contaminants from the diverse sources highlighted so far. Urban stream pollution also adversely affects river-dependent livelihood and has been reported to generate livelihood-related conflicts over limited access to good quality water [8]. Immediate and direct health impacts are linked to polluted urban streams because they provide harborage and conduce environment for pathogens such as bacteria, protozoa, viruses and parasites [9].

Beside water supply, urban streams and rivers, also play a critical role in pollution containment by serving as a continuous and dynamic biophysical treatment system primarily through sedimentation and biodegradation. However, under the stress of urbanization and associated activities, urban streams have experienced declining quality, alteration of biodiversity and changes in ecosystem functions [10]. Higher nutrient concentrations due to stream pollution usually leads to increased nutrient uptake by microbes and algae [5], [10]. However, over time the self-purification of the stream is overwhelmed, thus leading to algal bloom and ultimately, eutrophication.

While surface waters generally have an inbuilt capacity to regenerate themselves through several physical and biochemical processes such as sedimentation, oxidation, dilution, biodegradation, ion exchange and adsorption, the current rate of surface water degradation is beyond the self-purification capacity of these water bodies. As a result, many of these streams have experienced progressive but irreversible change in both water quality and aquatic ecosystem. The process of biodegradation of organic fractions of influent wastewater and runoff exerts enormous oxygen demand on the stream ecosystem, which ultimately results in the depletion of dissolved oxygen which in turn manifests in temporal and longitudinal oxygen sag in the stream. The dissolved oxygen in water is usually prevented from reaching a dangerously low level by the re-oxygenation process comprising of aquatic photosynthesis, atmospheric rea-aeration and natural runoff [6], [11]. Hence, the ability of the stream to sustain its self-purification capacity depends on the rate of oxygen replenishment of dissolved oxygen which is required by aquatic microbes to decompose organic matter. Besides, the survival of aquatic organisms and maintenance of aquatic biodiversity is dependent on sufficient supply of dissolved oxygen which must not drop below 5 mg/L for the survival of fish [12].

The rate of re-aeration in streams is dependent on several external factors such as flow depth, water temperature and barometric pressure [13]. Additionally, hydraulic parameters such as flow velocity determine the rate of sedimentation of organic solids, thus resulting in benthic oxygen demand (BOD) hotspots under tranquil conditions, while turbulent mixing encourages pollution dispersion and reaeration [14]. Depending on the flow hydraulics, turbulent mixing increases the exposed surface area of contact between air and water, leading

https://doi.org/10.4314/njt.v44i3.12

to air entrainment and subsequent dissolution of oxygen in water [15]. Most empirical re-aeration models are based on fluid-channel properties such as flow velocity, flow depth and channel slope while a few others incorporate Froude Number and hydraulic radius. This clearly shows that the rate of re-aeration is heavily dependent on flow conditions. Re-aeration studies are generally interested in the rates of stream re-aeration and how they affect the post-contamination stream water quality with focus on dissolved oxygen and biochemical oxygen demand. However, no serious attempt has been made to explore how water quality can affect stream re-aeration rate, though a few hints exist. Churchill et al (1962) as cited by [16] observed that water stagnation and thermal stratification can lower re-aeration rates However, no systematic attempt was made to build this effect into their model or even quantify it. A recent study by Singh et al [17] has established a strong connection between rate of oxygen dissolution and water quality parameters such as dissolved salt concentration, biochemical oxygen demand and biochemical oxygen demand. Hence, this study was aimed at establishing a relationship between re-aeration coefficient (k_2) and water quality parameters such as total dissolved solids, electrical conductivity, pH, suspended solids, water temperature and heavy metals. It is expected that the findings from this study may precipitate a paradigm shift from the traditional approach of modelling re-aeration based on only hydraulic factors to incorporating water quality parameters the models.

2.0 METHODOLOGY

2.1 Description of Study Area

Enugu State lies between longitudes 7^0E to 7.45^0E and latitudes 6.00^0N to 7.00^0N of the equator (Figure 1). It is the capital of Enugu State located in southeastern Nigeria. The average temperature is 26.4°C and the average annual rainfall is about 1719 mm. It has two distinct seasons namely, the rainy season spanning from March to November and the dry season spanning from December to February. Ekulu Stream in Enugu flows through the heart of the metropolis and is essential to agricultural, residential water supply, and local ecosystems. However, its water quality has drastically declined due to urbanization, fast population expansion, increase in pollution sources, including household waste, agricultural runoff and industrial discharges. Aquatic life, public health, and the stream's innate capacity to purify itself and rebound from pollution are all at risk due to this degradation. Developing sustainable water management plans requires an understanding of the major factors influencing the stream's potential for self-purification. The Ekulu Stream is subject to clear seasonal fluctuations in a tropical climate. Because of its location in a densely populated metropolitan region, it is vulnerable to a complicated mix of pollution sources, such as surface runoff from informal settlements, industrial effluents, municipal sewage, and waste from abattoirs. The Ekulu Stream receives both point and diffuse non-point pollution which create complicated interactions that defy standard water quality models, in contrast to many Western rivers where point-source contamination predominates [18]. Additionally, the coal-rich geology of the Ekulu region in southeast Nigeria raises the possibility of interactions between anthropogenic pollutants and natural mineral leaching that could affect self-purification processes in ways not yet described in the literature.

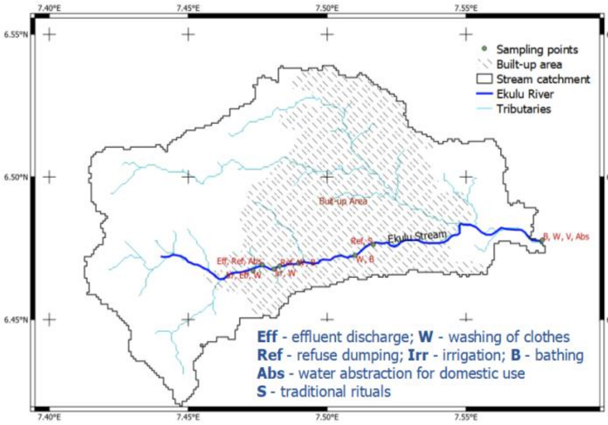

Figure 1: Map of stream and catchment area

2.2 Sample Collection and Analysis (Water and Soil)

The sampling sites were selected based on accessibility criteria. The inter-distance between sites was measured using a GPS tracking system, with spatial validation conducted via Google Earth. Geographical coordinates were recorded using an iPhone 11 equipped with multi-GNSS capability (GPS, GLONASS, Galileo, QZSS, and BeiDou). The device provides an estimated horizontal positional accuracy of approximately 3–5 m and vertical accuracy of approximately 5–10 m under open-sky conditions. Positioning performance is enhanced through Assisted-GPS (A-GPS), Wi-Fi positioning, and sensor fusion (accelerometer, gyroscope, and compass) in iOS 17.1.2. Water and soil samples were collected from ten designated sampling locations as given in Table 1. Temperature and pH were determined in-situ using a calibrated mercury thermometer with a precision of ±0.1°C at a depth of 30 cm below the water surface and a portable pH

https://doi.org/10.4314/njt.v44i3.12

meter (Hanna Instruments HI98107) calibrated with buffer solutions at pH 4.0, 7.0, and 9.2 respectively. A conductivity meter (Hanna HI98311) calibrated with a 0.01M KCl solution was used to determine electrical conductivity (EC), and the results were expressed in µS/cm. Total dissolved solids (TDS) was measured gravimetrically by filtering 100 mL samples through 0.45µm glass fiber filters, evaporating the filtrate at 180°C and measuring the residue (with an accuracy of ±1 mg). Total solid was determined by evaporating unfiltered sample to constant weight at 103–105°C in pre-weighed crucibles. Dissolved oxygen (DO) was measured using Winkler titration method. Concentrations of heavy metal (Ni, Pb, Cd, Fe and As) in water and sediment samples were determined using Buck atomic absorption spectrophotometer (AAS) model 210 VGP. Nickel, lead, cadmium and iron were tested at wavelengths of 232, 283.3, 228.85 and 248.3 nm respectively. To guarantee data dependability, all analyses were carried out in triplicate using the proper quality control procedures, such as reference material analysis and blank determinations. While laboratory analyses were finished within six hours of sample collection to maintain sample integrity, field measurements were carried out between 8:00 and 10:00 AM to reduce the impacts of diurnal variation. One mL of nitric acid was added to the samples to keep them in solution and prevent adsorption throughout the heavy metals sampling process.

Table 1: Sampling location and prevalent activities observed

Coordinates	Activities in the area	Interstation spacing (km)	Color
N6^0 28' 1" E7^0 28' 24"	Farming/irrigation effluent discharge laundry	0.3	Brownish
N6^0 28' 4" E7^0 28' 19"	Farming(irrigation), effluent discharge, laundry	0.35	Brownish
N6^0 28' 1" E7^0 28' 56"	Farming/irrigation laundry Building construction	0.3	Brownish
N6^0 27' 58" E7^0 29' 2"	Farming/irrigation laundry Construction of buildings.	0.25	Clear & brownish
N6^0 28' 0" E7^0 28' 59"	Refuse dumping, Laundry and bathing Washing of tricycles	0.32	Clear and slightly brownish
N6^0 28' 5" E7^0 29' 8"	Refuse dumping, Laundry and bathing Washing of tricycles	0.37	-
N6^0 28' 11" E7^0 29' 23"	laundry Farming/irrigation Bathing/ Swimming.	0.32	Clear but grayish
N6^0 28' 14" E7^0 29' 23"	Washing of clothes. Farming/irrigation Bathing/ Swimming.	0.35	Clear but grayish
N6^0 28' 31" E7^0 30' 36"	Washing, Bathing/Swimming.	0.37	Clear but grayish
N6^0 28' 28" E7^0 30' 31"	Washing, Bathing/Swimming.	0.48	Clear but grayish

2.3 Estimation of Re-aeration Coefficient (K_2)

Ten (10) empirical equations were identified and used for the estimation of re-aeration coefficient of the stream as detailed in Table 2. The empirical equations express K_2 as a function of various combinations of flow velocity, channel bed slope, flow depth, Froude Number and hydraulic radius. The equations examined fall into four major categories. The first category is of the form $K_2 = \alpha\frac{U^\beta}{d^\gamma}$ which tends to represent the ratio between kinetic energy and potential energy of flow. The implicit assumption of these models is that the rate of re-aeration depends on the kinetic energy of flow which is directly proportional to velocity and, the degree of mixing penetration which depends on flow depth. E_2, E_4, E_7, E_8 and E_9 belong to this category of models. The second category of re-aeration models are those of the general form $K_2 = \alpha\frac{(US)^\beta}{d^\gamma}$. The product of flow velocity and bed slope (US) in the equation represents the intensity of flow, driving force, the erosive power of the water flowing down the slope as well the ability of the flowing water to generate mixing turbulence both in the bulk water phase and at the water-air interface. E_1, E_3, E_5 and E_6 belong to this category. The third category is similar to the first except that depth was replaced with hydraulic radius as seen in E_{10}. In order to apply these models, the relevant hydraulic

https://doi.org/10.4314/njt.v44i3.12

parameters were obtained at each of the ten selected sections of the stream reach. These models were chosen because of their ease of application, requirement of few and easy-to-measure field parameters and clarity of parameters.

The inter-distance between sites was measured using a GPS tracking system, with spatial validation conducted via Google Earth. Geographic coordinates (latitude and longitude) were recorded using an iPhone equipped with Google Maps for geolocation accuracy. Flow velocity was measured using the float method with the appropriate correction factors applied. Temporal parameters were recorded using a digital stopwatch with 0.1-second resolution and channel width was measured directly using a calibrated tape measure with a guide rope for cross-sectional alignment while obtaining depth profiles using a graduated wading rod and weighted tape measurements at predetermined transects.

Table 2: Summary of various re-aeration formulas used for analysis

S/N	Empirical Equation	Reference
1	$E_1 = k_2 = \frac{32.69U^{0.413}S^{0.273}}{d^{1.408}}$	[19]
2	$E_2 = k_2 = \frac{5.58U^{0.607}}{d^{1.689}}$	[19]
3	$E_3 = k_2 = \frac{186.07(US)^{0.5}}{d}$	[20]
4	$E_4 = k_2 = \frac{11.73U^{0.969}}{d^{1.673}}$	[21]
5	$E_5 = k_2 = \left[\frac{59.17(1+N^2)(US)^{0.375}}{d(0.9+N)^{0.5}}\right]\left[\frac{(coth4.1(US)^{0.125}}{(0.9+N)^{0.5}}\right]$	[22]
6	$E_6 = k_2 = \frac{173.01(US)^{0.404}}{d^{0.66}}$	[23]
7	$E_7 = k_2 = \frac{5.14U}{d^{1.33}}$	[24]
8	$E_8 = k_2 = \frac{6.91U^{0.73}}{d^{1.75}}$	[25]
9	$E_9 = k_2 = \frac{5.35U^{0.67}}{d^{1.85}}$	[25]
10	$E_{10} = k_2 = \frac{11.635U^{1.0954}}{R^{0.0016}}$	[26]

K_2 = re-aeration coefficient; U = velocity; d = flow depth; S = average bed slope; R = hydraulic radius; N = Froude number

2.4 Statistical Evaluation of Re-aeration Models

After obtaining the k_2 values at various sampling points using the ten empirical models, the performance of the models was evaluated using boxplots and hierarchical clustering to establish similarity between the models. The values of k_2 were then regressed against each of the hydraulic parameters namely, flow depth, velocity, bed slope and hydraulic radius to determine the influence of these parameters on the value of k_2 based on the R^2 values. To explore the interaction between re-aeration and water quality, the k_2 values at the ten sampling points were also correlated with heavy metal concentrations in water and stream sediment. Finally, a multiple regression between k_2 and physico-chemical water parameters namely, electrical conductivity, temperature, total solids, pH, total dissolved solids, dissolved oxygen and biochemical oxygen demand. The regression analysis allowed for interaction of various parameters in order to obtain the best relationship. The performance of the regression parameters was evaluated using p-value at 90, 95 and 99% confidence levels. while the performance of the models was evaluated using mean squared error (MSE), R^2 values and Akaike's AIC.

3.0 RESULTS AND DISCUSSION

3.1 Hydraulic Characteristics of Ekulu Stream

Table 3 shows that Ekulu Stream is a shallow perennial stream with flow depths ranging from 0.13 to 0.36 m and mean width of 6.51 to 9.8 m as at the time of the study which took place in the dry season of February 2024. Some of the hydraulics of the stream clearly support the two mechanisms of aquatic photosynthesis and atmospheric gas transfer responsible stream re-aeration [27]. It has been reported that the concentration of oxygen in water is highly dependent on and inversely proportional to flow depth [16]. The shallow nature of the stream is good for re-oxygenation by facilitating rapid mass transfer of air [28]. Shallow streams allow for deeper light penetration which enables photosynthetic aquatic organisms to generate free oxygen within the bulk water phase. Furthermore, the shallow depth also facilitates mixing of water and air due to turbulence. The shear interaction between the bottom layer of the flowing water and the stream bed also generates turbulent mixing which is easily transmitted through the entire vertical profile of shallow streams. Turbulence aids re-aeration by encouraging gas exchange between water molecules and the atmosphere [29]. A shallow depth also entails greater surface area per unit volume of water in contact with air as opposed to deeper water bodies and absence of stratification which results in greater oxygen deficit with depth [30]. All but one of the empirical models investigated contain depth as a variable, either directly or through incorporation of Froude number and eight of them express an inverse relationship between flow depth and re-aeration coefficient.

Table 3 shows that the stream flow velocity was quite low at the time of investigation, ranging from 0.15 to 0.45 m/s with sub critical Froude number ranging from 0.11 to 0.32. The velocity range of the stream is about two orders of magnitude higher that Oshika Lake in Rivers State Nigeria used by [31] in their re-aeration studies. However, they are within the range reported by [32] who used circular laboratory

https://doi.org/10.4314/njt.v44i3.12

channels, though of smaller flow depth. The sub-critical nature of the flow throughout the entire stretch of the stream investigated precludes the occurrence of hydraulic jump which facilitates vertical mixing and aeration [33]. However, the range of Froude number obtained for this stream has been reported to facilitate hyporheic flux. A strong positive correlation has been reported between Froude number up to 0.23 and hyporheic flux, while a 50% reduction in hyporheic flux when Froude number approaches 0.85 [33]. Several studies have shown that significant air entrainment and subsequent dissolution of oxygen is achieved in a hydraulic jump as flow regime changes from supercritical (Fr > 1) to sub-critical (Fr < 1) flow [27], [29]. The energy dissipated in the jump generates turbulent mixing that facilitates re-oxygenation. However, a hydraulic jump is most unlikely in Ekulu stream given that the flow regime is sub critical all through the stretch of interest.

Table 3: Hydraulic parameters obtained from the various parts of the stream

Sample station	Slope	Cross-sectional area (m^2)	Mean depth (m)	Velocity (m/s)	Mean width (m)	Depth to width ratio	Fr	Nature of flow
S1	0.00712	7.274	0.225	0.331	6.514	0.034	0.222	sub-critical
S2	0.00712	11.620	0.287	0.45	7.974	0.025	0.315	sub-critical
S3	0.00509	8.248	0.35	0.267	6.86	0.051	0.144	sub-critical
S4	0.00509	7.707	0.19	0.146	9.322	0.020	0.106	sub-critical
S5	0.00991	11.750	0.228	0.36	9.762	0.013	0.318	sub-critical
S6	0.00991	9.0696	0.357	0.42	6.308	0.056	0.224	sub-critical
S7	0.00521	8.887	0.211	0.236	8.17	0.025	0.164	sub-critical
S8	0.00521	9.373	0.287	0.266	6.32	0.045	0.158	sub-critical
S9	0.00515	6.256	0.205	0.332	9.214	0.022	0.234	sub-critical
S10	0.00515	5.216	0.218	0.316	8.966	0.012	0.296	sub-critical

3.2 Re-aeration Coefficients of Ekulu Stream Based on Various Empirical Models

The re-aeration coefficient of Ekulu stream as computed using the various models ranged from 0.072 to 49.44 day^{-1}. Figure 2 shows very wide variations of re-aeration coefficients estimated using the various models. The models of Churchill (E4) [21], Owens et al (E8 & E9) [25] and Bennett and Rathbun (E1 & E2) [19] gave the highest k_2 values ranging 57.11 to 18.90, 49.46 to 16.56, 47.95 to 15.40, 45.96 to 23.56 and 41.54 to 14.74 day^{-1} respectively. These five models also exhibited the widest variation of re-aeration coefficient along the stream with standard deviations of 12.83, 11.05, 10.68, 7.72 and 8.98 respectively. It is pertinent to note that E4, E8, E9 and E1 are functions of velocity and depth only, while E2 is a function of velocity, slope and depth. The models of Krenkel and Orlob (E6), Cadwallader and McDonnel (E3) and Dobbins (E5) gave intermediate ranging from 40.15 to 28.44, 40.1 to 27 and 26.28 to 18.6 day^{-1} values with lower variability along the stream [20], [22], [23]. These three models are a function of velocity, bed slope and flow depth. It seems that the inclusion of slope in the re-aeration model tends to moderate the value of K_2 computed in streams with mild slope like the Ekulu stream. The model of Agunwamba et al (E10) gave the lowest values of K_2 ranging from 4.87 to 1.42 day^{-1} as well as the lowest variability along the stream stretch. The model of Agunwamba et al is a function of velocity and hydraulic radius only.

Among all ten models investigated only this model incorporated hydraulic radius while excluding flow depth and assigning an exponent greater than unity to flow velocity. One would have argued that the wide gap between the performance of this mode and other models may stem from the use of a secondary parameter whose physical meaning is not as precise as other parameters such as velocity, slope and flow depth. Moreover, Wei et al [34] observed that the limitation of the applicability of the hydraulic radius in the past stems from the fact that boundary shear stress is not uniformly distributed over the wetted perimeter. However, studies have shown that the hydraulic radius is not a pure geometric parameters but also represents the physical measure of the size of eddies in the bulk flow which play an important role in turbulent mixing [35]. Hence, the incorporation of hydraulic radius in Agunwamba's model is a justifiable effort. However, it does seem that the resultant model suppressed the importance of this quantity based on the assigned exponent of 0.006. Further examination of the results obtained showed that exclusion of hydraulic radius from the model will not cause any significant change (+0.2%) in the value of re-aeration coefficient. Since the stream channel in question approximates a wide channel with $R \approx d$, it

https://doi.org/10.4314/njt.v44i3.12

can be seen that the model tends to obliterate the indispensable role of flow depth in stream re-aeration.

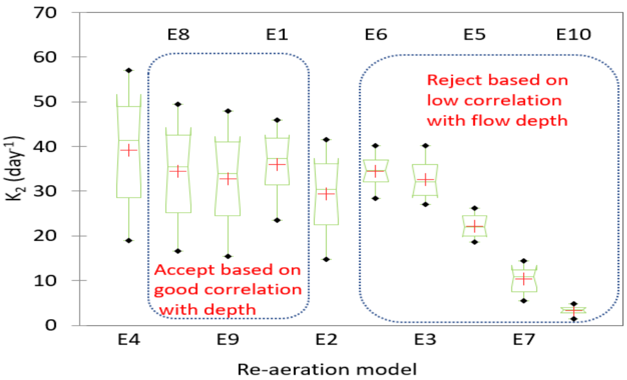

Figure 2: Box plots of re-aeration coefficients based on various empirical models

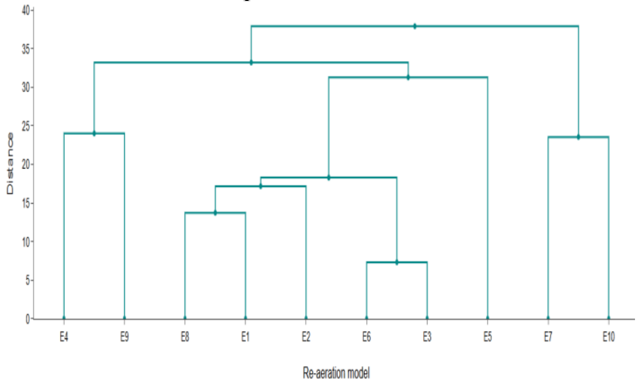

Figure 3: Re-aeration model clusters

A cluster analysis of the various re-aeration model resulted in five distinct groupings as follows: E1, E2, E8; E3, E6; E4, E8 and E7, E10 (Figure 3). While some of the groupings can be interpreted easily, some others present challenges in interpretation. The similarity between E1 and E2 may have resulted from being derived by the same author and calibrated with the same data, while the similarity between E2 and E8 could be because they have the same structure ($K_2 = n\frac{U^{\alpha}}{d^{\beta}}$) and use the same parameters. However, E8 generally have higher values of K2 than E2 because it has a higher model constant and also assigns a higher importance to velocity. E4 and E9 have the same structure as E2 and E8 but were grouped separately. E3 and E6 are grouped together because they have the same structure ($K_2 = n\frac{(US)^{\alpha}}{d^{\beta}}$) and both produced similar K2 values of of 32.7 and 34.5 day^{-1}. E7 and E10 were grouped together because they both assigned equal importance to velocity, but their computed K2 values differ widely (10.3 and 3.3 day^{-1} respectively). E5 was not grouped with any other model because it has an entirely different structure from all the other models, involving Froude number and a trigonometric function.

3.3 Relationship Between Re-aeration Coefficients and Hydraulic Parameters

All the models considered incorporated flow depth (d) directly except E10 which approximates flow depth with hydraulic radius. From Figures 4a and 4b, E1, E2, E8 and E9 have an inverse relationship with flow depth and good coefficients of determination (R^2 = 0.80, 0.72, 0.63 and 0.72 respectively); E4 and E5 have an inverse relationship with flow depth and moderate coefficients of determination (R^2 = 0.42 and 0.43); E3, E6 and E7 have an inverse relationship with flow depth and low coefficients of determination (R^2 = 0.22, 0.04 and 0.24); while E10 a direct relationship with flow depth and a low coefficient of determination (R^2 = 0.15). Given that Ekulu stream is a shallow channel, flow depth is expected to play a critical role in re-oxygenation such that shallower sections of the stream should have higher rates of re-aeration as confirmed by Leu et al. [36]. The poor correlation of E3, E6, E7 and E10 with flow depth suggests that they are not good for prediction of K_2 in the stream investigated. All the models have very poor positive relationship with velocity except E1 with a poor negative relationship and E10 with very good positive relationship (R^2 = 0.99). As stated earlier this is because E10 suppressed the role of flow depth in the re-aeration process, but exaggerated the role of flow velocity. In the same vein, all the models were poorly correlated with bed slope except E10 (R^2 = 0.5). Though hydraulic radius is not present in all the models except E10, K_2 values computed using the models were inversely related to hydraulic radius except E10. Though the correlation was generally poor, E1, E2, E8 and E9 exhibited moderately good relationship with hydraulic radius (R2 = 0.37, 0.38, 0.33 and 0.4) despite not containing the parameter. This suggests that these models mirrored the hydro-dynamics of the stream better than the rest of the models and are therefore more suitable for describing and predicting the re-aeration of Ekulu stream with average K_2 values of 35.99, 29.48, 34.46 and 32.84 day^{-1}.

3.4 Relationship Between Re-aeration Coefficients and Water Quality Parameters

Dissolved oxygen along the sampled stream stretch ranged from 2.4 to 5.4 mg/L indicating that there are points of critical oxygen sag possibly resulting from effluent discharge and refused dumping. However, there was weak correlation between dissolved oxygen and k_2 values. Figures 5a and 5b expose a persistent

https://doi.org/10.4314/njt.v44i3.12

trend between water quality parameters and the rate of surface re-oxygenation in Ekulu stream. Apart from E1 and E3, all the models used in this study produced k_2 values that have positive relationship with pH of water. Though studies on the effect of pH on re-aeration rates are largely absent in the literature, Zang et al [37] reported a positive correlation between pH and dissolved oxygen concentration in aquacultural and non-aquacultural waters. The values of coefficient of determination however, suggest that the pH of water which ranged from 6.5 to 7.2 may not significantly alter the rate of re-aeration under the conditions prevalent in this study. In all cases, the value of k_2 exhibited an inverse relationship with total dissolved solids. This suggests that dissolved solids can interfere with the rate of re-oxygenation either by directly reducing the rate of oxygen dissolution or by exerting oxygen demand on the bulk flow. However, as in the case of pH, the range of total dissolved solids present in the stream (28 – 320 mg/L) was not considered sufficient to significantly alter the rate of surface re-oxygenation. Water temperature (20.2 to 21.8 ºC) was found to have a direct relationship with re-aeration rate. Like most other rate constants, it is expected that value of k_2 will increase with temperature. The positive effect of temperature on re-aeration rates can be attributed to a reduction in water viscosity following an increase in temperature, which then increases the rate of oxygen diffusion by reducing resistance at the bulk liquid interface with air [38]. Hill et al. [39] also reported significant sensitivity of re-aeration to temperature in a Northeastern US stream where temperature varied seasonally by up to 20 ºC.

Though individual water quality parameters did not significantly affect re-aeration rates as earlier discussed, Table 4 shows that the interactive effects of various water quality parameters might significantly affect the rates of re-aeration. Between 55 and 91% of the variation in the value of K_2 can be explained by a linear combination of various water quality parameters and their interactions, specifically TDS and the interaction of electrical conductivity and temperature (EC*Temp). Terms that bring significant explanation to the variation in K_2 have been rendered in bold face in Table 4. TDS featured in six of the linear models and was significant in all; while EC*Temp featured in six of the linear models, but was significant in five at 95% confidence level. In all cases, K_2 was inversely proportional to TDS, but directly proportional to EC*Temp. At higher temperatures, water molecules gain kinetic energy, thereby increasing their mobility.

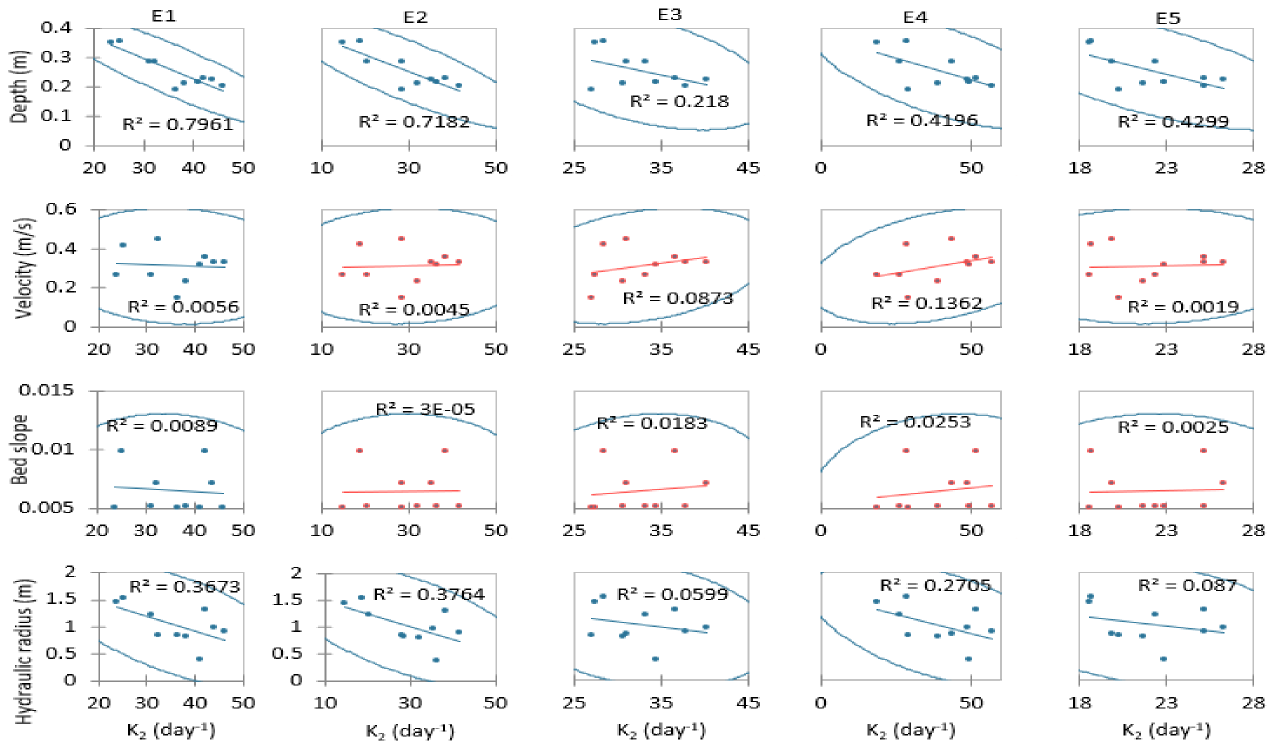

Figure 4a: Regression of re-aeration models with hydraulic parameters (E1 - E5)

https://doi.org/10.4314/njt.v44i3.12

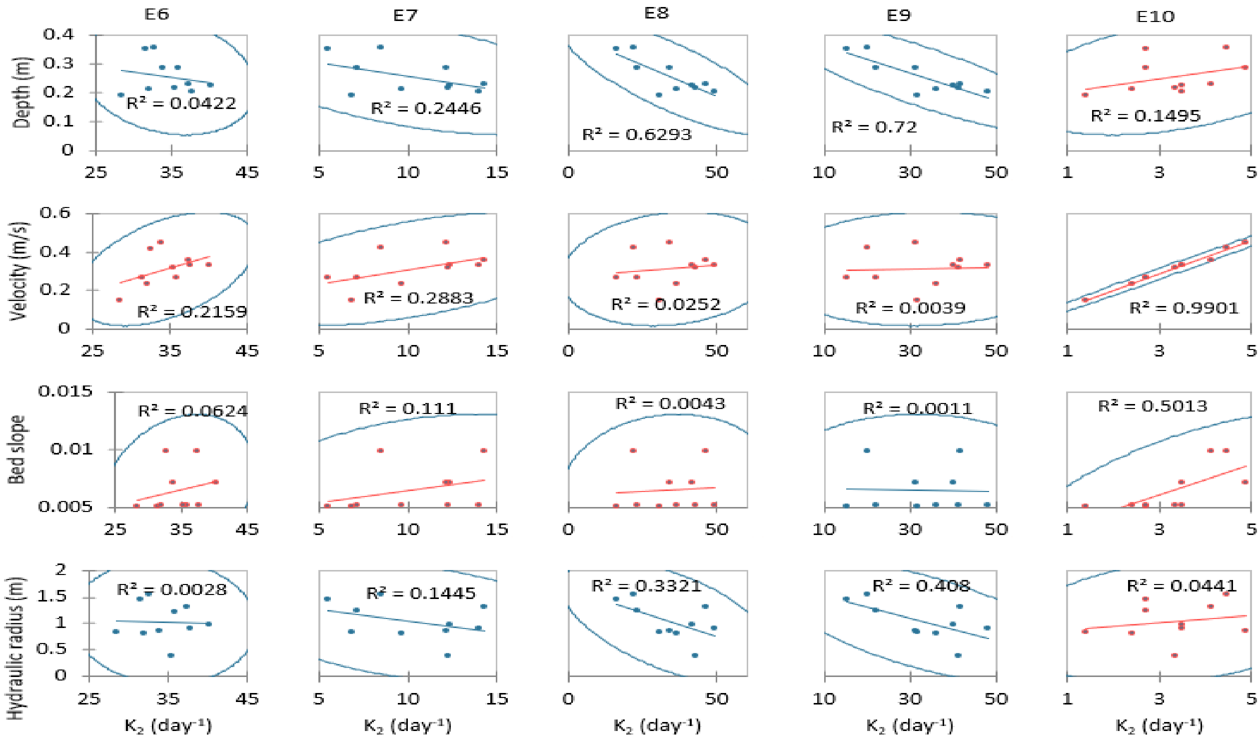

Figure 4b: Regression of re-aeration models with hydraulic parameters (E6 - E10)

The synergistic effect of electrical conductivity and temperature could stem from the fact that high electrical conductivity of water facilitates absorption of heat from the sun which in turn increases the rate of re-aeration. On the other hand, increased temperature by 1°C leads to an increase in electrical conductivity by 2% [40]. The foregoing also suggest that specific water quality parameters are also affected by stream channel morphology and hydraulics which formed the basis of all the re-aeration models used in this study. It is also important to note that re-aeration models incorporating only velocity and flow depth (E2, E4, E7, E8 & E9) exhibited the best liner relationship with water quality parameters with p-values of 0.012, 0.001, 0.000, 0.005 and 0.014 at 95% confidence level and R^2 values of 0.72, 0.88, 0.9, 0.78 and 0.71 respectively.

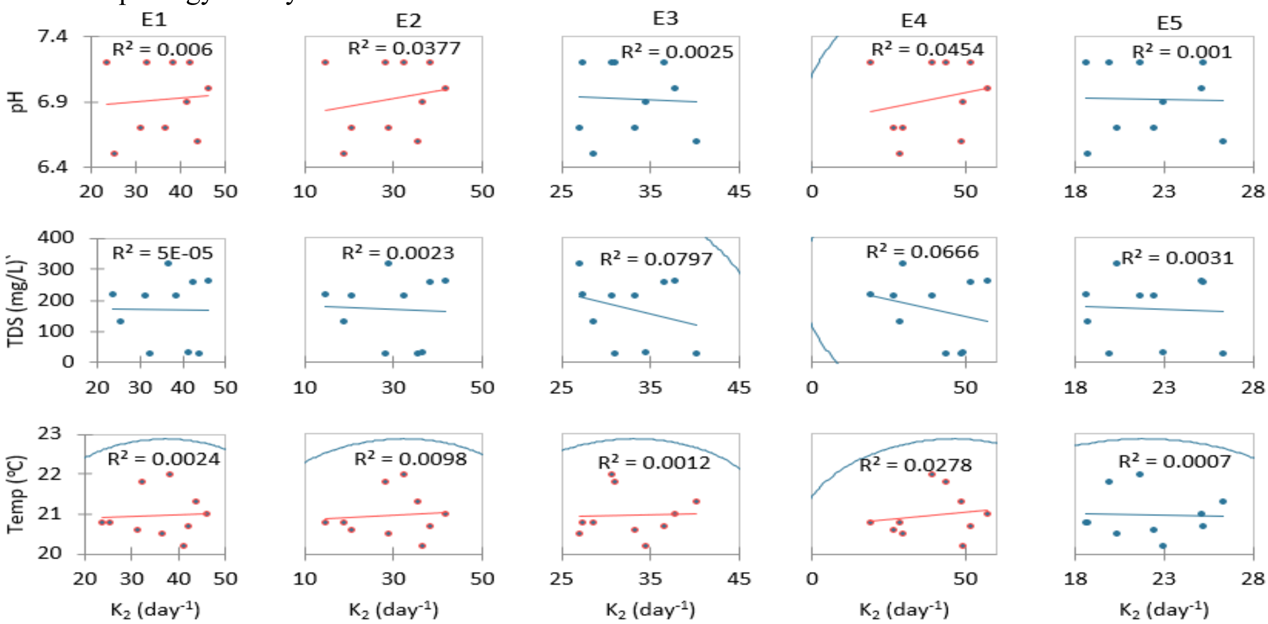

Figure 5a: Regression of re-aeration coefficient and water quality parameters (E1 to E5)

https://doi.org/10.4314/njt.v44i3.12

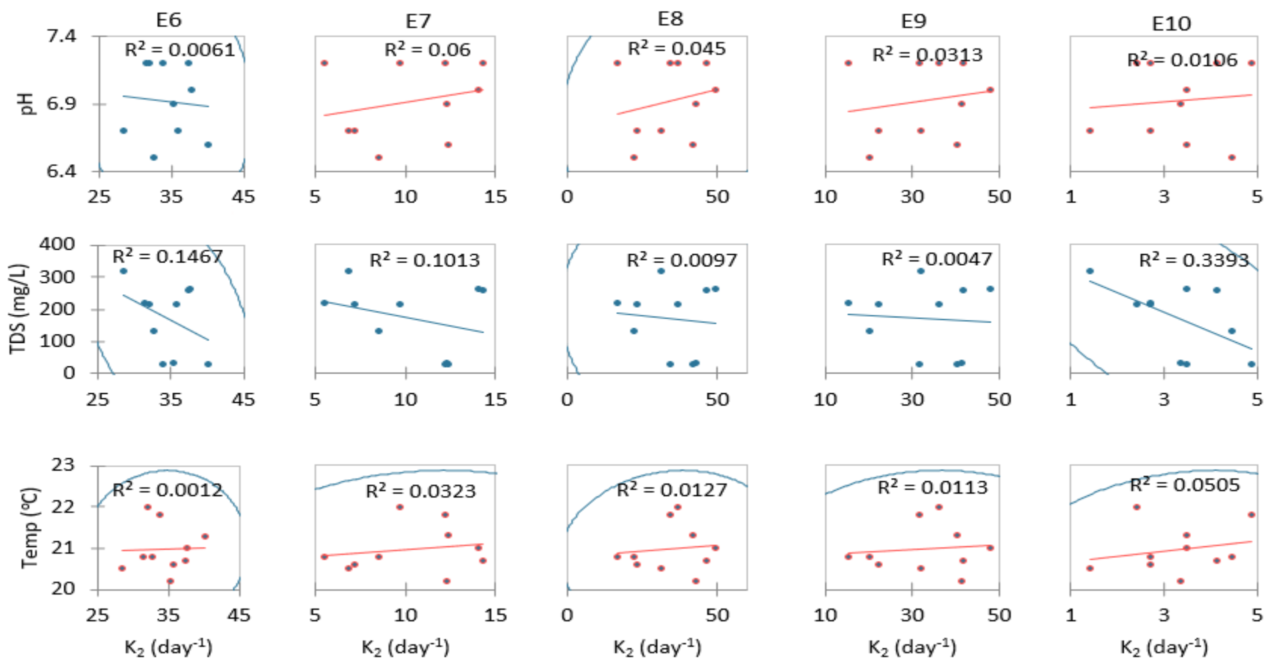

Figure 5b: Regression of re-aeration coefficient and water quality parameters (E6 to E10)

Table 4: Regression of re-aeration coefficients with significant water quality parameters

Class	Equation	Regression Parameters	P-value	Parameter Effect	R^2	MSE	Akaike's AIC	Regression p-value	Remark
(1) $K_2 = f(U, S, d)$ *Hydraulic-geometric*	E_1	**EC*Temp**	0.021**	direct	0.554	34.23	37.77	0.059	Not significant
		TDS	0.022*	inverse					
	E_3	**TDS*EC**	0.009**	direct	0.667	8.779	24.16	0.021	Significant
		TDS*TS	0.008**	inverse					
	E_5	**TDS*EC**	0.017*	direct	0.583	4.114	16.58	0.047	Significant
		TDS*TS	0.017*	inverse					
	E_6	**TDS*EC**	0.01*	direct	0.692	4.792	18.10	0.016	Significant
		TDS*TS	0.009**	inverse					
(2) $K_2 = f(U, d)$ *Hydraulic*	E_2	**TDS**	0.004**	inverse	0.715	29.56	36.31	0.012	Significant
		EC*Temp	0.004**	direct					
	E_4	**TDS**	0.00**	inverse	0.879	25.69	34.90	0.001	Significant
		EC*Temp	0.00**	direct					
	E_7	**TDS**	0.001***	inverse	0.913	1.112	3.50	0.000	Significant
		EC*Temp	0.001***	direct					
	E_8	**TDS**	0.002**	inverse	0.775	35.30	38.07	0.005	Significant
		EC*Temp	0.002**	direct					
	E_9	**TDS**	0.005**	inverse	0.706	43.01	40.05	0.014	Significant
		EC*Temp	0.005**	direct					
(3) $K_2 = f(U, R)$ *Hydraulic-geometric*	E_{10}	**TS*EC**	0.019*	inverse	0.715	0.392	-6.93	0.012	Significant
		TDS*EC	0.016*	Direct					

* 90% confidence level
** 95% confidence level
*** 99% confidence level

All re-aeration models except E9 and E10 produced K_2 values that are negatively correlated with Fe and As; while all except E9 produced K_2 values that are positively correlated with Ni (Figure 6). While the correlation of K_2 with Fe ranged from very low (-0.066 for E6) and high (0.535) for E9, correlation with Ni was high (0.585 to 0.80) except for E9 and E10. The negative correlation between K_2 and Fe suggests either

https://doi.org/10.4314/njt.v44i3.12

competitive uptake or depletion of dissolved oxygen due to the oxidation of Fe. On the other hand, the presence of Ni in the stream seem to enhance re-aeration rate by acting as a catalyst for oxygen dissolution. While there are not many literature backing for this inference, Liang et al [41] reported that nickel-dioxygen species can act as a catalyst for oxygen dissolution.

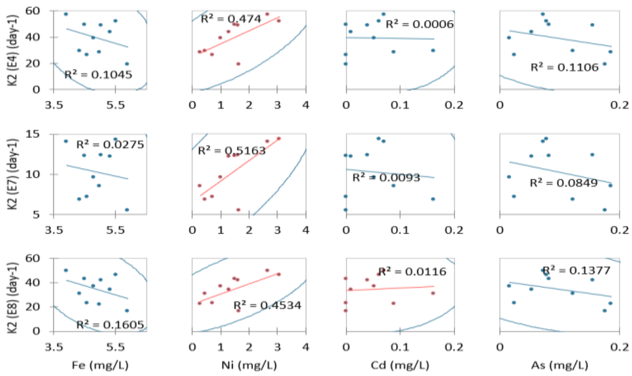

Figure 6: Relationship between re-aeration coefficient and heavy metals

4.0 LIMITATIONS OF THE STUDY

It is pertinent to acknowledge the limitations associated with using empirical models derived from entirely different environment and hydrodynamic settings to the study location. This is in additions to the limitations imposed by laboratory experiments from which the data used to develop some of the models were obtained. It is hoped that further studies will remedy these obvious limitations.

5.0 CONCLUSION

Results from the study indicate that the Stream is already manifesting acute dissolved oxygen deficit due to pollution resulting from effluent discharge and other anthropogenic activities.

The models of Churchill (E4), Owens et al (E8 & E9) and Bennett and Rathbun (E1 & E2) gave the highest k2. The values of k2 from all models except that of Agunwamba were inversely correlated with flow depth. Eight of the models (E2, E4 to E10) produced k2 values that have positive relationship with pH of water. TDS, EC and temperature were generally well correlated with k_2 values suggesting that water quality significantly influences the rate of re-aeration. Re-aeration models incorporating only velocity and flow depth exhibited the best linear relationship with water quality parameters. K_2 values were generally positively correlated with Ni, but negatively correlated with As, Fe and Pb. This study has clearly shown that there is a strong link between water quality and re-aeration rate. It is expected that this new finding has identified a new exploratory variable which will improve the prediction of re-aeration of surface waters. Furthermore, the re-aeration rate and self-purification capacity of the stream can be enhanced by curbing indiscriminate effluent discharge and waste dumping into the stream. One way to do this is to activate relevant environmental and effluent discharge regulations. Further studies could integrate water quality both in the experimental and modelling phase with a view to developing more accurate re-aeration models.

REFERENCES

[1] A. F. Danelon, F. G. Augusto, and H. F. S. Spolador, "Water resource quality effects on water treatment costs: An analysis for the Brazilian case," *Ecol. Econ.*, vol. 188, p. 107134, Oct. 2021, doi: 10.1016/j.ecolecon.2021.107134.

[2] J. I. Price and M. T. Heberling, "The Effects of Source Water Quality on Drinking Water Treatment Costs: A Review and Synthesis of Empirical Literature," *Ecol. Econ.*, vol. 151, pp. 195–209, Sep. 2018, doi: 10.1016/j.ecolecon.2018.04.014.

[3] F. Sheldon, C. Leigh, W. Neilan, M. Newham, C. Polson, and W. Hadwen, "Urbanization," in *Approaches to Water Sensitive Urban Design*, Elsevier, 2019, pp. 229–248. doi: 10.1016/B978-0-12-812843-5.00011-3.

[4] I. R. Abubakar, "Exploring the determinants of open defecation in Nigeria using demographic and health survey data," *Sci. Total Environ.*, vol. 637–638, pp. 1455–1465, Oct. 2018, doi: 10.1016/j.scitotenv.2018.05.104.

[5] T. Cai, S. Y. Park, and Y. Li, "Nutrient recovery from wastewater streams by microalgae: Status and prospects," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 360–369, Mar. 2013, doi: 10.1016/j.rser.2012.11.030.

[6] Y. Wen, G. Schoups, and N. van de Giesen, "Organic pollution of rivers: Combined threats of urbanization, livestock farming and global climate change," *Sci. Rep.*, vol. 7, no. 1, p. 43289, Feb. 2017, doi: 10.1038/srep43289.

[7] U. Etemire and N. Uwoh Sobere, "Improving public compliance with modern environmental laws in Nigeria: looking to traditional African norms and practices," *J. Energy Nat. Resour. Law*, vol. 38, no. 3, pp. 305–327, Jul. 2020, doi: 10.1080/02646811.2020.1751970.

[8] B. N. Onyima, L. N. Nwabueze, C. F. Nnadozie, G. O. Omovoh, T. Mmachaka, B. O. Omovoh, F. O. Arimoro, J. E. Uku, F. C.

https://doi.org/10.4314/njt.v44i3.12

Akamagwuna, G. O. Onyima, and O. N. Odume, “Livelihood risks arising from urban river pollution in selected marginal communities in the Federal Capital Territory, Nigeria,” *Urban Ecosyst.*, vol. 28, no. 1, p. 33, Feb. 2025, doi: 10.1007/s11252-024-01646-7.
[9] E. J. Isukuru, J. O. Opha, O. W. Isaiah, B. Orovwighose, and S. S. Emmanuel, “Nigeria’s water crisis: Abundant water, polluted reality,” *Clean. Water*, vol. 2, p. 100026, Dec. 2024, doi: 10.1016/j.clwat.2024.100026.
[10] Gao, Y. Huang, Y. Zhi, J. Yao, F. Wang, W. Yang, L. Han, D. Lin, Q. He, B. Wei, and K. Grieger, “Assessing the impacts of urbanization on stream ecosystem functioning through investigating litter decomposition and nutrient uptake in a forest and a hyper-eutrophic urban stream,” *Ecol. Indic.*, vol. 138, p. 108859, May 2022, doi: 10.1016/j.ecolind.2022.10885 9.
[11] S. Zhu and S. Heddam, “Prediction of dissolved oxygen in urban rivers at the Three Gorges Reservoir, China: extreme learning machines (ELM) versus artificial neural network (ANN),” *Water Qual. Res. J.*, vol. 55, no. 1, pp. 106–118, Feb. 2020, doi: 10.2166/wqrj.2019.053.
[12] O. Bozorg-Haddad, M. Delpasand, and H. A. Loáiciga, “Water quality, hygiene, and health,” in *Economical, Political, and Social Issues in Water Resources*, Elsevier, 2021, pp. 217–257. doi: 10.1016/B978-0-323-90567-1.00008-5.
[13] Z. Wang, D. Pu, J. Zheng, P. Li, H. Lü, X. Wei, M. Li, D. Li, and L. Gao, “Hypoxia-induced physiological responses in fish: From organism to tissue to molecular levels,” *Ecotoxicol. Environ. Saf.*, vol. 267, p. 115609, Nov. 2023, doi: 10.1016/j.ecoenv.2023.115609.
[14] C. Gualtieri and T. Mihailovic, *Fluid Mechanics of Environmental Interfaces*. CRC Press, 2012.
[15] J. Dufek, T. Esposti Ongaro, and O. Roche, “Pyroclastic Density Currents,” in *The Encyclopedia of Volcanoes*, Elsevier, 2015, pp. 617–629. doi: 10.1016/B978-0-12-385938-9.00035-3.
[16] S. Arora and A. K. Keshari, “Modelling re-aeration of rivers using predictive models and developed ANN models under varying hydrodynamic conditions,” *Hydrol. Sci. J.*, vol. 67, no. 15, pp. 2294–2309, Nov. 2022, doi: 10.1080/02626667.2022.2138402.
[17] V. Singh, R. K. Srivastava, and A. K. Bhatt, “Dissolved Oxygen and Water Quality,” in *Battling Air and Water Pollution*, Singapore: Springer Nature Singapore, 2025, pp. 111–120. doi: 10.1007/978-981-96-4375-2_8.
[18] L. K. Jeje and S. I. Ikeazota, “Effects of Urbanisation on Channel Morphology: The Case of Ekulu River in Enugu, South Eastern Nigeria,” *Singap. J. Trop. Geogr.*, vol. 23, no. 1, pp. 37–51, Mar. 2002, doi: 10.1111/1467-9493.00117.
[19] J. P. Bennett and Rathbun, “Reaeration in open channel flow,” 1972.
[20] T. E. Cadwallader and A. J. McDonnell, “A multivariate analysis of reaeration data,” *Water Res.*, vol. 3, pp. 731–742, 1969.
[21] M. A. Churchill, H. L. Elmore, and R. A. Buckingham, “The prediction of stream reaeration rates,” *Am. Soc. Civ. Eng.*, vol. 88, no. SA-4, pp. 1–64, 1962.
[22] W. E. Dobbins, “Closure to ‘‘BOD and oxygen rela_tionship in streams,” *J. Sanit. Eng. Am. Soc. Civ. Eng.*, vol. 91, pp. 49–55, 1965.
[23] P. A. Krenkel and G. T. Orlob, “Turbulent diffusion and the reaeration coefficient,” *Trans. Am. Soc. Civ. Eng.*, vol. 128, pp. 293–334, 1963.
[24] W. B. Langbein and W. H. Durum, “The aeration capacity of streams,” 1967. doi: 10.3133/cir542.
[25] M. Owens, R. Edward, and J. Gibbs, “Some Reaeration Studies In Streams,” *Air Water Pollut.*, vol. 8, pp. 469–486, 1964.
[26] J. C. Agunwamba, C. N. Maduka, and A. M. Ofosaren, “Analysis of pollution status of Amadi Creek and its management,” *J. Water Supply Res. Technol. - Aqua*, vol. 55, no. 6, pp. 427–435, Sep. 2006, doi: 10.2166/aqua.2006.036.
[27] S. Mondal, R. Das, S. Das, and S. Mukherjee, “Experimental investigation of dissolved oxygen improving aeration efficiency by hydraulic jumps,” *Flow Meas. Instrum.*, vol. 100, p. 102715, Dec. 2024, doi: 10.1016/j.flowmeasinst.2024.102715.
[28] M. R. Andersen, T. Kragh, and K. Sand-Jensen, “Extreme diel dissolved oxygen and carbon cycles in shallow vegetated lakes,” *Proc. R. Soc. B Biol. Sci.*, vol. 284, no. 1862, p. 20171427, Sep. 2017, doi: 10.1098/rspb.2017.1427.
[29] S. Kucukali and S. Cokgor, “An Experimental Investigation of Reaeration and Energy Dissipation in Hydraulic Jump,” 2020, pp. 127–136. doi: 10.1007/978-3-030-37105-0_11.
[30] B. S. R. V. Prasad, P. D. N. Srinivasu, P. S. Varma, A. V. Raman, and S. Ray, “Dynamics

of Dissolved Oxygen in Relation to Saturation and Health of an Aquatic Body: A Case for Chilka Lagoon, India," *J. Ecosyst.*, vol. 2014, pp. 1–17, Feb. 2014, doi: 10.1155/2014/526245.

[31] J. Ugbebor, J. C. Agunwamba, and V. E. Amah, "Determination of reaeration coefficient k2 for polluted stream as a function of depth, hydrualic radius, temperature and velocity," *Niger. J. Technol.*, vol. 31, no. 2, pp. 174–178, 2012.

[32] J. C. de Souza Inácio Gonçalves, A. Silveira, G. B. Lopes Júnior, M. S. da Luz, and A. L. A. Simões, "Reaeration Coefficient Estimate: New Parameter for Predictive Equations," *Water, Air, Soil Pollut.*, vol. 228, no. 8, p. 307, Aug. 2017, doi: 10.1007/s11270-017-3491-5.

[33] Y. Liu, Z. Tang, L. Huang, T. Stoesser, and H. Fang, "On the role of the Froude number on flow, turbulence, and hyporheic exchange in open-channel flow through boulder arrays," *Phys. Fluids*, vol. 36, no. 9, Sep. 2024, doi: 10.1063/5.0222673.

[34] M. Wei, N.-S. Cheng, and Y. Lu, "Revisiting the concept of hydraulic radius," *J. Hydrol.*, vol. 625, p. 130134, Oct. 2023, doi: 10.1016/j.jhydrol.2023.130134.

[35] G. Gioia and F. A. Bombardelli, "Scaling and Similarity in Rough Channel Flows," *Phys. Rev. Lett.*, vol. 88, no. 1, p. 014501, Dec. 2001, doi: 10.1103/PhysRevLett.88.014501.

[36] H.-G. Leu, C. F. Ouyang, and T.-Y. Pai, "Effects of flow velocity and depth on the rates of reaeration and bod removal in a shallow open channel," *Water Sci. Technol.*, vol. 35, no. 8, 1997, doi: 10.1016/S0273-1223(97)00151-0.

[37] C. Zang, S. Huang, M. Wu, S. Du, M. Scholz, F. Gao, C. Lin, Y. Guo, and Y. Dong, "Comparison of Relationships Between pH, Dissolved Oxygen and Chlorophyll a for Aquaculture and Non-aquaculture Waters," *Water, Air, Soil Pollut.*, vol. 219, no. 1–4, pp. 157–174, Jul. 2011, doi: 10.1007/s11270-010-0695-3.

[38] B. O. L. Demars and J. R. Manson, "Temperature dependence of stream aeration coefficients and the effect of water turbulence: A critical review," *Water Res.*, vol. 47, no. 1, pp. 1–15, Jan. 2013, doi: 10.1016/j.watres.2012.09.054.

[39] N. B. Hill, S. J. Riha, and M. T. Walter, "Temperature dependence of daily respiration and reaeration rates during baseflow conditions in a northeastern U.S. stream," *J. Hydrol. Reg. Stud.*, vol. 19, pp. 250–264, Oct. 2018, doi: 10.1016/j.ejrh.2018.09.006.

[40] M. Hayashi, "Temperature-Electrical Conductivity Relation of Water for Environmental Monitoring and Geophysical Data Inversion," *Environ. Monit. Assess.*, vol. 96, no. 1–3, pp. 119–128, Aug. 2004, doi: 10.1023/B:EMAS.0000031719.83065.68.

[41] Y. Liang, S.-H. Shi, R. Jin, X. Qiu, J. Wei, H. Tan, X. Jiang, X. Shi, S. Song, and N. Jiao, "Electrochemically induced nickel catalysis for oxygenation reactions with water," *Nat. Catal.*, vol. 4, no. 2, pp. 116–123, Jan. 2021, doi: 10.1038/s41929-020-00559-w.

.

https://doi.org/10.4314/njt.v44i3.12