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Development of deoxygenation and reaeration rate coefficients for a small tributary of river Hindon, U.P., India

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Abstract

Dissolved oxygen (DO) is an important parameter indicating the health of the stream. There is a continual utilization (deoxygenation) and/or replenishment (reaeration) of dissolved oxygen due to the influx of waste load in the stream at different points. Estimating deoxygenation and reaeration rate coefficients, using indirect approach supplemented by calculations, provides one of the most reliable techniques. In addition, laboratory and field experiments can provide information on relative ranges of deoxygenation and reaeration rates.

In the present study, the concept of Streeter and Phelps (1925) with exponential law of non-settleable BOD and laboratory experiments have been applied to estimate the reaeration rate and deoxygenation rate coefficients, respectively, for different reaches of the Kali River, U.P., India. A total of 270 field data sets have been collected during the period from March 1999 to February 2000. A predictive equation has been proposed to obtain the reaeration equation for the River Kali using a least square algorithm that minimizes error estimates and improves correlation between observed and computed reaeration coefficients.

INTRODUCTION

The presence of dissolved oxygen in water is the primary criterion of the water quality of streams. To model and allocate waste loads in a stream, it is necessary to estimate the deoxygenation rate coefficient (K_1) and reaeration coefficient (K_2). The DO model contemplates the decay of biodegradable organic matter and the reaeration process is given by:

$$D = \frac{K_1 L_0}{K_2 - K_1}(e^{-K_1 t} - e^{-K_2 t}) + D_0 e^{K_2 t} \qquad (1)$$

Where,
D = dissolved oxygen (DO) deficit of water (gO_2/m^3).
D_0= initial oxygen deficit in the water (downstream of effluent outfall) (gO_2/m^3)
L_0= initial BOD concentration in the water (downstream of effluent discharge) (gO_2/m^3)
t= time of travel in the river interpreted as t=x/v, where x is the distance downstream of the point

K_1= rate coefficient of biochemical decomposition of organic matter (T^{-1}, usually day^{-1})
K2= reaeration rate coefficient (T-1, usually day-1) at test temperature T (o C). The value of $(K_2)_T$ is related to the value $(K_2)_{20}$ as follows:

$$(K_2)_T = (K_2)_{20} * 1.024^{(T-20)} \tag{2}$$

The K1 values are computed by laboratory experiments of the field samples collected periodically. However, for field and experimental appraisal of K2, there are three basic approaches, namely, the dissolved oxygen balance technique (Streeter and Phelps, 1925; Churchill et al, 1962, Jha et al., 2000), the distributed equilibrium technique (Zogorski and Faust, 1973; Edwards et al, 1961) and tracer techniques (Tsivoglou and Wallace, 1972) in practice. In addition to these, several empirical equations exist to predict K1 and K2. A review of these equations indicate that K1 and K2 have been often related to different stream variables including mean flow velocity, shear stress velocity, bed slope, flow depth and Froude number. While this abundance reflects a great deal of effort, it also reflects the lack of an accurate general formula. In view of this persisting uncertainty, it's essential to accomplish in-stream measurements to evaluate K1 and K2 in addition to the use of predictive equations.

The objective of the present study is to look into the estimation of deoxygenation and reaeration coefficients for different reaches of river Kali and to develop a simplified predictive equation for K_2 using different stream variables including mean flow velocity, shear stress velocity, bed slope, flow depth, Froude number. The field measurements have been undertaken to obtain observed K_1 and K_2 values using laboratory experiments and the dissolved oxygen balance technique (DOBT) (Streeter and Phelps, 1925). However, the database is used to derive an empirical relationship that minimizes the errors and provides an improved correlation coefficient.

STUDY AREA AND THE DATA BASE

The River Kali is an important left bank tributary of the River Hindon originating near the Saharanpur district in western Uttar Pradesh, India (Figure 1). The river traverses a course of 125 km before meeting the River Hindon and has a total catchment area of about 750 km^2. It lies between $29^0 13'$ to 30^0 N latitude and $77^0 35'$ to $77^0 45'$ E longitude. The mean rainfall over the basin is 1000 mm which occurs mainly during the monsoon period and the major land use is agriculture. The soils of the area are loam to silty loam and are normally free from carbonates.

The Kali River has its distinct capacity to purify the organic matters disposed into the flowing water through reaeration process. To allocate waste loads and to compute dissolved oxygen in the stream, it is essential to measure the reaeration rate in different reaches of the Kali River. Sampling of all the field data (270 points) on flow depth, velocity and slope from twenty-two locations (sixteen river points and six effluent points) was accomplished during March'99- February'2000. The mean velocity varies between

0.2 to 0.5 m/s and the mean flow depth increases towards downstream from 0.0 to 1.0 m due to inflow of point and non-point sources of discharge into the stream.

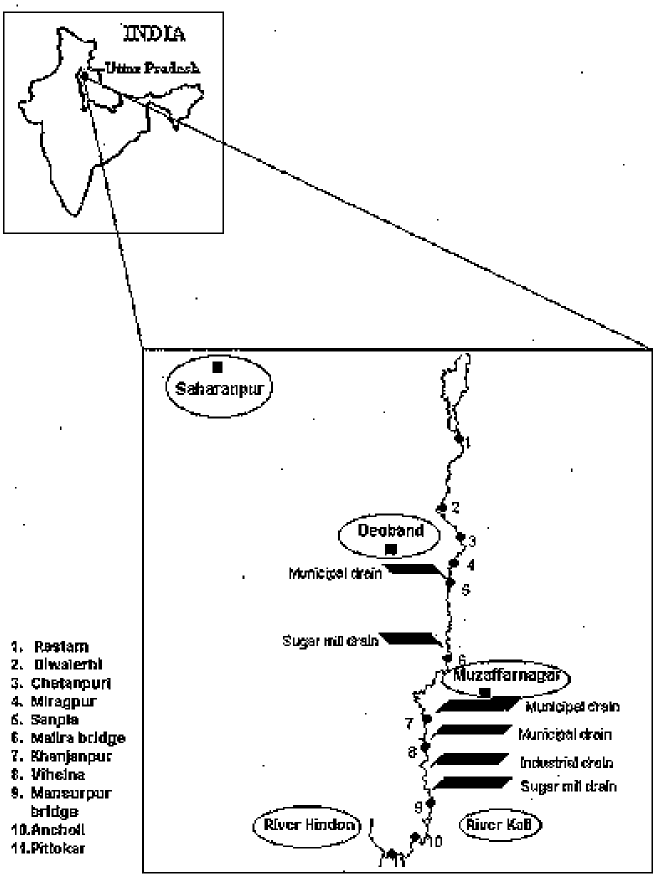

Figure 1. Location of river Kali in India.

ESTIMATION OF DEOXYGENATION (K_1) AND REAERATION (K_2) RATE COEFFICIENTS

Deoxygenation Rate Coefficient (K_1)

The deoxygenation rate coefficient, K_1 (1/day), has been determined from the BOD_5 values and estimated travel time between stream reaches (Texas Water Development Board, 1971). The biochemical oxygen demand (BOD_5) of un-preserved stream water samples has been obtained by measuring the DO of river samples (collected from the field) and blank samples on the 0th day and the 5th day. The blank sample is the distilled water that is used for dilution of polluted river water. The samples were kept in incubators for five days at 20^{o} C to obtain 5th day DO. The equation used to calculate BOD_5 can be written as:

$$BOD_5 = \left[(D_0 - D_1) - (C_0 - C_1)\right] f_c \qquad (3)$$

in which, D_0 and D_1 are the DO of stream water samples for 0^{th} day and 5^{th} day, C_0 and C_1 are the DO of blank samples for 0^{th} day and 5^{th} day and f_c is the decimal fraction of sample used. The bi-monthly representative biochemical oxygen demand variation in the River Kali is shown in Figure 2.

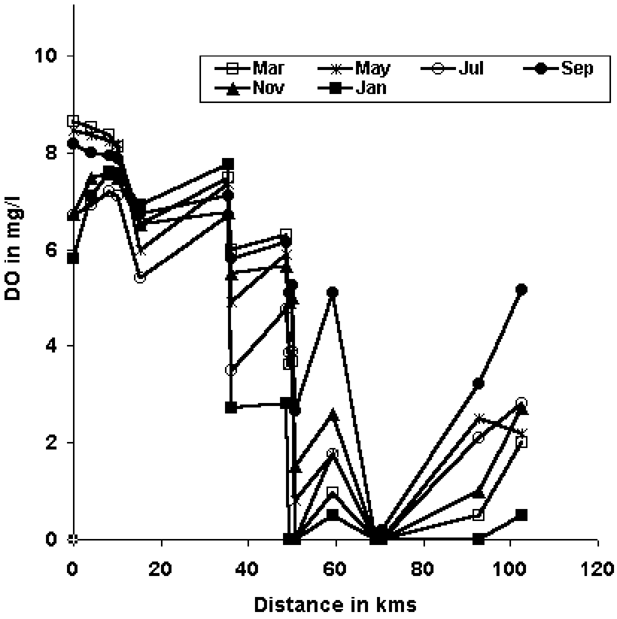

Figure 2. Bi-monthly representative biochemical oxygen demand variation.

The BOD_5 obtained for different reaches of River Kali were plotted on a log scale (Y-axis) and the travel time is plotted on a normal scale (x-axis). The slope of the line provides the values of the deoxygenation coefficient (K_1).

Reaeration (K_2) Rate Coefficient

This technique consists of selecting a reach of the stream, measuring all the sources and sinks of dissolved oxygen (DO) with the exception of reaeration, and determining by difference the reaeration needed to give the DO concentration observed at the downstream end of the reach. Under controlled conditions where all the sources and sinks of DO are monitored, the DO balance technique can be effectively used as compared to the distributed equilibrium and tracer techniques. In small streams, it is very difficult to deaerate the river water to bring DO equal to zero as is essentially required in the distributed equilibrium technique. Also, it is not suitable to use radioactive tracers, which directly affect the aquatic life in small streams and that require high precision in handling, monitoring and computation using sophisticated high cost equipment. Further, the DOBT used in the present study is a simple, more accurate and cost effective method.

The water quality variables monitored between different reaches of River Kali are: dissolved oxygen (DO) of upstream, downstream and incoming tributaries; biochemical oxygen demand (BOD) of upstream, downstream and incoming tributaries; photosynthesis by plants; respiration by plants, and water temperature.

The "light and dark" bottle method was used to determine photosynthesis and respiration rates. Six bottles each of dark and light colour were dipped in the flowing water on a sunny day. At every hour one set of bottles (one light and one dark) was taken out of the stream and preserved using Manganous sulfate solution and alkali-iodide-azide reagent (APHA, 1985) for DO measurement. It was observed that the algae present in river water are very limited and do not cause any variation in DO due to photosynthesis and respiration processes. Thus, the net effect of photosynthesis and respiration has been found to be negligible and is considered as zero in the present study.

The dissolved oxygen (DO) of upstream, downstream and incoming tributaries or effluent in each reach has been measured by titration of the preserved water samples collected from the field using standard methods (APHA, 1985). The samples so preserved in the field were brought to the laboratory, in sampling kits maintained at 4^{o}C, for detailed chemical analysis. DO determination was based on the Winkler method with the addition of divalent manganese solution and alkali-iodide-azide reagent. Figure 3 illustrates the representative dissolved oxygen variation bi-monthly in the River Kali.

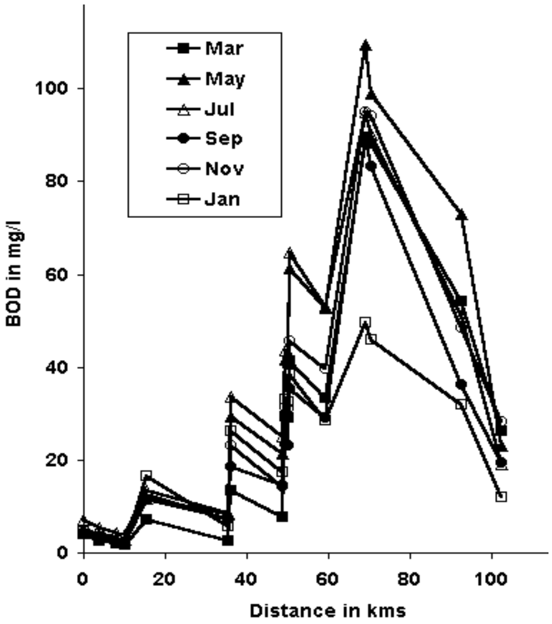

Figure 3. Bi-monthly representative dissolved oxygen variation in the River Kali.

Temperature is an important factor affecting solution of gases, their escape from water into the atmosphere, and the process of chemical and biochemical self-purification. The water temperature for each sample was monitored in the field just before preserving the samples for DO analysis in the laboratory.

With the above inputs the general mass balance equation 1 for DOBT has been used in the present study. By the measurement of all the variables except K_2 in equation 1 and using the Newton Raphson algorithm, the values of K_2 have been estimated for each data set. In the rest of the study, the K_2 that is estimated by this technique is termed the observed K_2.

Table 1. Developed Predictive Reaeration Equations.

Sl No	Scientists	Reaeration equation
1.	O'Connor and Dobbins (1958)	$K_2 = 3.90V^{0.5}H^{-1.5}$
2.	Churchi11 et al. (1962)	$K_2 = 5.010V^{0.969}H^{-1.673}$
3.	Krenkel and Orlob (1962)	$K_2 = 173(SV)^{0.404}H^{-0.66}$
4.	Owens et al. (1964)	$K_2 = 5.35V^{0.67}H^{-1.85}$
5.	Langbein and Durum (1967)	$K_2 = 5.14VH^{-1.33}$
6.	Cadwallader and McDonnell(1969)	$K_2 = 186(SV)^{0.5}H^{-1}$
7.	Thackston and Krenkel (1969)	$K_2 = 24.9(1+F_r{}^{0.5})V_*H^{-1}$
8.	Parkhurst and Pomeroy (1972)	$K_2 = 23(1+0.17F_r{}^2)(SV)^{0.375}H^{-1}$
9.	Tsivoglou and Wallace (1972)	$K_2 = 31200SV$ for $Q < 0.28m^3/\sec$ $K_2 = 15200SV$ for $Q > 0.28m^3/\sec$
10.	Smoot (1984)	$K_2 = 543S^{0.6236}V^{0.5325}H^{-0.7258}$
11.	Moog and Jirka (1998)	$K_2 = 1740V^{0.46}S^{0.79}H^{0.74}$ for $S > 0.00$ $K_2 = 5.59S^{0.16}H^{0.73}$ for $S < 0.00$

Here, V= velocity of stream water in m/s, H= flow depth in m, S= slope, V_*= friction velocity in m/s, and F_r = Froude number.

DEVELOPMENT OF PREDICTIVE EQUATION FOR K_2

Numerous equations employing mean flow velocity, shear stress velocity, bed slope, flow depth and Froude number have been developed after the classical work of Streeter and Phelps (1925) to estimate the stream reaeration coefficient, K_2 (Table 1). Based on the field data such as velocity, depth and slope measured in different reaches of River Kali a predictive equation has been developed on the basis of following equation:

$$K_2 = aV^bD^c \tag{4}$$

in which, v is the velocity of flow in cumec., D is the depth of water, and a, b, and c are coefficients.

Model Testing

The performance of the developed predictive equation based on equation 4 has been evaluated using mean multiplicative errors statistics and correlation coefficient.

The mean multiplicative error (MME), K_P/K_M, which is considered to provide a better basis for assessing the impact of inaccuracies in predicting reaeration coefficients (Moog and Jirka, 1998) may be defined as:

$$MME = \exp\left[\frac{\sum_{i=1}^{N}\left|\ln\left({K_P}/{K_M}\right)_i\right|}{N}\right] \tag{5}$$

In water quality studies, correlation analysis can be used to measure the strength and statistical significance of the association between two or more random water quality variables. The value of this coefficient, r, ranges from –1 to 1. A value of r close to –1 indicates a strong negative correlation, i.e. the value of y decreases as x increases. When r is close to 1 there is a strong positive correlation between x and y, both variables increase or decrease together. The closer the value of r is to zero the poorer the correlation. When the data sets meet the assumptions of normality and independence, Pearson's Product Moment Correlation Coefficient r is normally used as given below:

$$r = \frac{n\sum_{i=1}^{n} K_{p_i} K_{M\,i} - \sum_{i=1}^{n} K_{P\,i} \sum_{i=1}^{n} K_{M\,i}}{\sqrt{[n\sum_{i=1}^{n} K_{P\,i}^{\,2} - (\sum_{i=1}^{n} K_{P\,i})^2][n\sum_{i=1}^{n} K_{M\,i}^{\,2} - (\sum_{i=1}^{n} K_{M\,i})^2]}} \tag{6}$$

in which K_P and K_M are the predicted and computed reaeration coefficients, n is the no. of data.

ANALYSIS OF RESULTS

The deoxygenation rate coefficient (K_1) values computed by the laboratory experiment, as explained earlier, have been used along with other water quality variables computed/monitored in the field to compute the reaeration coefficient. The mean (μ), standard deviation (σ) and frequency of each value have been determined and % frequency of the value lying within different intervals is given below.

S.No.	Intervals	Percentage Frequency Distribution
1.	μ-3σ	0
2.	μ-2σ	0
3.	μ-σ	18.75
4.	μ	37.50
5.	μ+σ	33.00
6.	μ+2σ	6.25
7.	μ+3σ	4.1

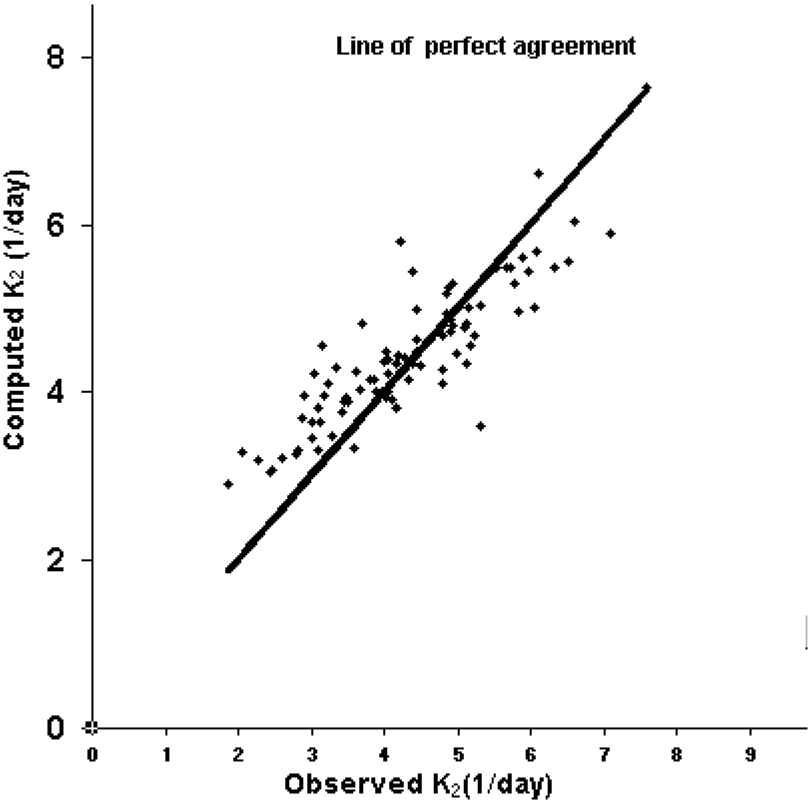

Figure 4. Plot of observed K_2 versus computed K_2.

It can be seen from the table that most of the values lie within the interval of (μ -σ) and (μ +σ). The reaeration coefficient (K_2) values have been computed from the predictive equation (4) using field data sets generated for the River Kali. A plot of observed K_2 versus computed K_2 shows close agreement from the line of prefect agreement in all the cases (Figure 4). The predictive equation (as given below) has been derived using flow depth and velocity variables to estimate K_2 for the River Kali. The other stream variables such as Froude number, friction velocity and slope are interrelated with flow depth and velocity and thus, have been eliminated in the present study. Least absolute deviation regression has been used to generate a linear regression of $\ln K_2$ on $\ln V$ and $\ln H$. Rather than the ordinary minimisation of squared errors, this procedure minimises the absolute value of $\ln K_2$ and thus produces a minimal error and better modification. The equation evolved is as follows:

$$K_2 = 5.792 V^{0.5} H^{-0.25} \qquad (7)$$

(r^2 =0.965)

As can be seen from Figure 4, the K_2 values estimated by equation 7 show close agreement with the line of perfect agreement. The error estimates MME is found to be minimum and the correlation coefficient is found to be improved for the values of K_2

determined by equation 7.The MME value, which is considered to be the most accurate criteria for error estimation, is given as below. Further, to test the successful functional representation of predictive equations, correlation coefficients were determined for full data set.

S.No.	Performance evaluation	Value
1.	Mean multiplicative error (MME)	1.13
2.	Correlation coefficient (r)	0.74

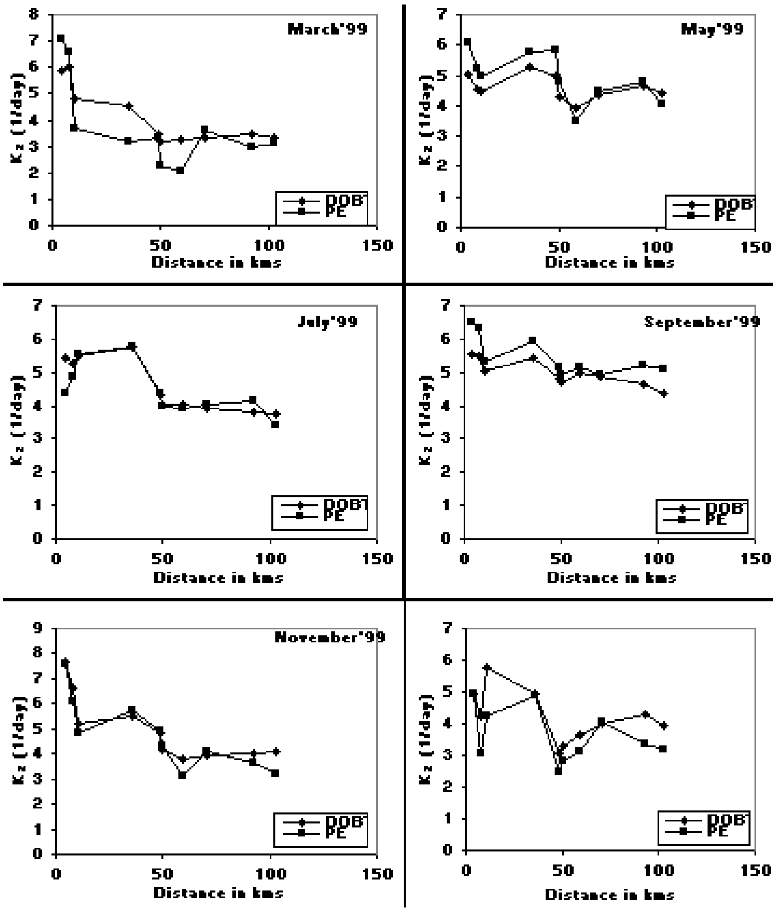

Figure 5. A comparison of computed K_2 values and observed K_2 from field data for six representative data sets.

A comparison of computed K_2 values using predictive equation and observed K_2 from field data for six representative data sets are shown in Figure 5. The results obtained are encouraging and highlight the better performance of the refined predictive equation. In general, higher K_2 values are obtained in the upper reaches of the River Kali in comparison to the lower reaches, with a variation from 3.0 to 8.0 per day.

CONCLUSIONS

Eighty nine percent values of deoxygenation rate coefficient (K_1) have been found to lie between (μ -σ) and (μ +σ).

Analysis of existing reaeration equation revealed a generally poor performance with under / over prediction. It is desirable to refine existing reaeration equations for every individual stream. Also, it is not necessary to use interrelated variables in predictive equations, which may be converted in the form of flow depth and velocity.

The developed predictive reaeration equation developed for the River Kali exhibits favorable results and can be used as a substitute for extensive field surveys. The equation may be useful in other rivers having similar hydraulic, geographic and climatic conditions.

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