DEVELOPMENT OF REAERATION COEFFICIENT FOR INDIAN CONDITIONS USING MATHEMATICAL APPROACH AND FIELD STUDIES

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PREFACE

The presence of dissolved oxygen in water is the primary criterion to evince the water quality of streams. A stream may receive point and non-point pollution from various sources like municipal, industrial and agricultural land on its way to the downstream. The rate of oxygen utilization (deoxygenation) by aquatic microbes present in these pollutants, to metabolize organic matter, oxidize reduced nitrogen, and oxidize reduced minerals species such as ferrous iron increases the oxygen demand in the water and deteriorates its water quality. However, the dissolved oxygen concentrations in stream are mainly dependent on biochemical oxygen demand (BOD) as the process of deoxygenation, nitrification, salinity, temperature, plant and animal respiration, benthal demand, atmospheric reaeration and photosynthesis among other factors.

The oxygen utilized by the pollutant increases the oxygen deficit in the water. Reaeration is an important physical process of oxygen transfer between the water surface and the atmosphere that reduces the dissolved oxygen concentration deficit of the stream. The reaeration rate in a stream depends on the hydraulic parameters, river characteristics and temperature. The higher reaeration rate indicates that the stream has high waste assimilative capacity.

Considering the importance of reaeration rate, a study based on pioneer work of Streeter and Phelps (1925) has been conducted by the Institute in Kali River of Western Uttar Pradesh, India. Also, most commonly used predictive equations based on hydraulic parameters developed after Streeter and Phelps to predict reaeration rate have been applied. The performance of all the predictive equations has been evaluated by error estimation (standard error, normal mean error and mean multiplicative error) and correlation with the estimated reaeration rate by Streeter and Phelps approach. A new predictive equation based on hydraulic parameters has been developed to determine the reaeration coefficient for river Kali under different flow conditions.

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ABSTRACT

The river pollution is one of the serious concerns in the present scenario of water resources development. Rivers are one of the most potent sources of water. However, it is being observed that the river quality has been deteriorating for long due to steady growth of industries, urbanization, increasing population and use of chemicals and fertilizers for agriculture. There are number of constitutents which determine the quality of water, however, dissolved oxygen (DO) is the most important parameter indicating the health of a stream. There is a continual replenishment (reaeration) or utilization (deoxygenation) of dissolved oxygen due to inflow of waste load at different points in a stream. When a waste load is discharged into a flowing stream, it is mainly subjected to advection, dispersion and reaction kinetics. Waste Load Allocation (WLA) studies provide information to assist in making affective decisions on levels of treatment required for a source or sources of pollutant loads.

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). Rate coefficients, in contrast to loads, sources and sinks generally cannot be directly measured under natural conditions. Indirect measurements, supplemented by calculations provide one of the most reliable techniques for estimating rate coefficients. In addition, laboratory and field experiments can provide information on relative ranges of reaeration and deoxygenation rates. Numerous equations employing depth, velocity and slope have been developed to estimate the stream reaeration and deoxygenation rate coefficient. This leads to uncertainties in modeling analysis because these equations are empirical in nature and may yield very different K_1 & K_2 values for the same stream. Realizing the uncertainties involved in determining K_1 & K_2, many modelers have resorted to model calibrations as a way of adjusting values. In fact, in the pioneer work of stream analysis by Streeter and Phelps (1925), K_2 was evaluated indirectly by using DO budget and the K_1 was evaluated by carrying out laboratory and field experiments.

In the present study, the concept of Streeter and Phelps (1925) with exponential law of non-settleable BOD has been applied to determine the reaeration coefficients and deoxygenation rate coefficients for different reaches of river Kali, a highly polluted river of western Uttar Pradesh (India). The most commonly used predictive equations developed earlier for small streams having flow less than 10 m^3/s and depth below 2 m were also tested. The predictive equations have been evaluated using statistics including normal mean error (NME), standard error (SE) and mean multi-plicative errors (MME). The results obtained from these equations have been compared with the field observations carried out at frequent intervals and from Streeter & Phelps technique and a correlation between the two has been obtained. A new predictive equation has been developed for Kali River under different flow conditions and evaluated for errors and correlation with the mass balance approach of Streeter and Phelps.

1.0 INTRODUCTION

Every stream has its own capacity to purify the organic matters disposed into the flowing water, generally known as "self purification capacity" or "waste assimilative capacity" of the stream. The most important consideration in determining the waste assimilative capacity of a stream is its ability to maintain an adequate dissolved oxygen concentration. Dissolved oxygen concentrations in stream are controlled by atmospheric reaeration, photosynthesis, plant and animal respiration, benthal demand, biochemical oxygen demand as the process of deoxygenation, nitrification, salinity, and temperature among other factors. Fig.1 illustrates the important factors affecting the dissolved oxygen in the stream.

The most accurate oxygen balance would consider all significant factors. However, many of the factors are very difficult, if not impossible, to determine accurately; and unless unusual conditions are present, fairly reliable predictions of the "self purification process" of a water body can be obtained through simulation of the simultaneous processes of reaeration (natural or artificial) and deoxygenation as measured by the biochemical oxygen demand (BOD). Reaeration is the process of oxygen exchange between the atmosphere and water body in contact with the atmosphere and the deoxygenation is the oxygen demand by the organic matters present in the stream.

There are two basic methods of estimating values of the deoxygenation (K_1) and reaeration (K_2) rate constant to estimate oxygen balance in the stream:

1. If in-stream measurement data of DO and BOD are obtained then the model can be calibrated, by fitting the calculated curves to the measured ones. This can be easily done for de-oxygenation rate constant of BOD (K_1) but the value of reaeration coefficient K_2 can be found only by trial-error model simulations or by using a respective fitting algorithm, built in models of practical use. These processes are considered in the traditional BOD-DO model (Streeter and Phelps, 1925) in the mathematical form as:

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

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REAERATION

ORG-N

DI
S
S
O
L
V
E
D

O
X
Y
G
E
N

NH₃

CBOD

NO₂

ORG-P

NO₃

DIS-P

chl a
ALGAE

ORG-N- Organic-nitrogen
NH3   - Ammonia-nitrogen
NO2   - Nitrite-nitrogen
NO3   - Nitrate Nitrogen

ORG-P - Organic-phosphate
DIS-P - Dissolved-phosphate
chl a   - Chlorophyll
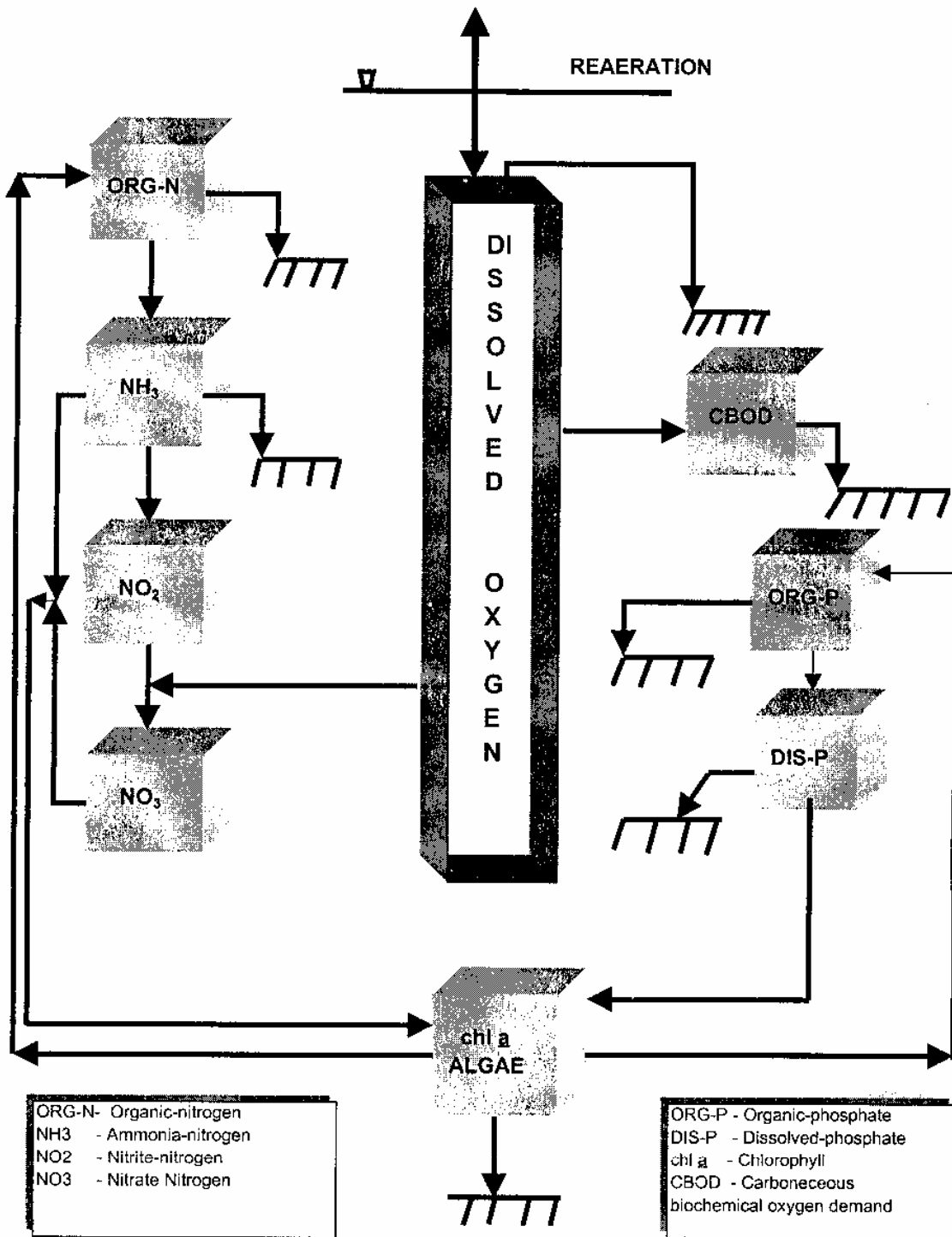CBOD - Carboneceous
biochemical oxygen demand

FIG.1: FLOW CHART OF DISSOLVED OXYGEN BALANCE

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in which, D= Dissolved oxygen deficit at time t (mg/l), K_1= Deoxygenation rate constant (1/day), t= travel time (days), L_0= Initial BOD (mg/l), D_O= Initial DO deficit (mg/l), K_2= reaeration coefficient (1/day).

2.   If access to measurement data is not possible then model parameters can be estimated using formulae and tables published in the relevant literature (Table 1).

1.1   Variables for Oxygen Mass Balance Approach

1.1.1   Deoxygenation Rate Constant (K_1)

The rate of oxygen utilisation (deoxygenation) due to biological activity is of particular importance in streams as the dissolved oxygen deficit in water reflects its quality. Biochemical Oxygen Demand (BOD) is the utilisation of dissolved oxygen by aquatic microbes to metabolise organic matter, oxidise reduced nitrogen, and oxidise reduced minerals species such as ferrous iron. Concentration of reduced minerals in waste streams are usually in consequential, and so BOD is commonly divided into two fractions; that exerted by carbonaceous matter (CBOD) and that exerted by nitrogenous matter (NBOD). When the concentration of dissolved oxygen in a stream is at the saturation level (this is normally the case when there is no oxygen demand exerted and no significant amount of algae present), the rate of transfer of oxygen across the air-water interface is zero. However, as oxygen demand is exerted due to carbonaceous and nitrogenous matter, the dissolved oxygen concentration is reduced below the saturation level and oxygen is transferred across the air-water interface and into the stream by re-aeration. Because waste waters are potentially high in BOD, and because dissolved oxygen concentration is used as a principal determinant of the health of an aquatic system, BOD is a widely applied measure of aquatic pollution.

It is essential to know the minimum concentration of dissolved oxygen occurred due to wastewater influx and its location in order to set the effluent quality standards and flow augmentation required if bio-degradable material in the effluent cannot be removed to a sufficient extent to meet a target dissolved oxygen level.

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The rate of oxygen utilisation due to biochemical oxygen demand (BOD) can generally be expressed as first-order bio-kinetic reaction:

$$\frac{\partial L}{\partial t} = -K_1 L_t \qquad \ldots 2$$

where, K_1 = BOD rate constant, base (e), mg/l, and L_t = Concentration of BOD(ultimate), mg/l, at time t.

The deoxygenation rate constant (K_1) has traditionally been determined in the laboratory; however, it is quite obvious that the rate of BOD exertion in a laboratory bottle is not necessarily the same as in a natural system. The value of K_1 not only depends on the nature of the waste material, but also is affected by mixing, deposition, and adsorption.

1.1.2 Reaeration Coefficient (K_2)

One of the major phenomena contributing to the biochemical oxidation in waters containing degradable materials is atmospheric reaeration. Many theories have been proposed and a large number of techniques and equations have been used to estimate the reaeration coefficient K_2; however, there is no universally accepted method for doing so (Moog and Jirka, 1998).

Reaeration is the process of oxygen exchange between the atmosphere and water body in contact with the atmosphere. Typically, the net transfer of oxygen is from the atmosphere into the water, since dissolved oxygen levels in most natural waters are below saturation. However, when photosynthesis produces supersaturated dissolved oxygen levels, the net transfer is back into the atmosphere.

In the biological treatment of wastewater, aeration is an important process employed to raise the dissolved oxygen (DO) level to allow aerobic bacteria to reduce biochemical oxygen demand of the effluent resulting in improvement in the water quality. The oxygen supplied must be at a rate sufficient to at least balance the rate of removal of the active biomass.

According to the two film theory (Lewis and Whiteman 1924; Eckenfelder and O'Connor 1961; Cleasby and Baumann 1968; Metcalf & Eddy Inc. 1979; Manual of Practice for water pollution control 1988), mass transfer occurs through the gas and liquid interface, through a laminar flow in the two films (one gas and one liquid) and through turbulent flow in the body of the liquid until a dynamic equilibrium is established. The rate of mass transfer, $\partial m/\partial t$, of oxygen from the

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atmosphere to the body of the turbulent liquid is generally proportional to the difference between the existing concentration C and the equilibrium or saturation concentration C* of oxygen in the liquid. It can be expressed as

$$\frac{\partial m}{\partial t} = k_L A(C^* - C) \qquad \qquad \dots 3$$

where, k_L= coefficient of diffusion of oxygen in the liquid; and A= area through which oxygen is diffusing. By noting

$$\frac{\partial m}{\partial t} = V \frac{\partial C}{\partial t} \qquad \qquad \dots 4$$

where, V= volume of the liquid,

Then it can be expressed as

$$\frac{\partial C}{\partial t} = (k_L \, A/V)(C^* - C) \qquad \qquad \dots 5$$

The parameter $k_L \, A/V$ is generally designated by $k_L a_T$, the oxygen transfer coefficient at test temperature T($^{\circ}$C). Upon integration of equation between the limits C=C_o at time t=0 and C=C_t at t= t, one obtains

$$k_L a_T = [\ln(C^* - C_o) - \ln(C^* - C_t)]/t \qquad \qquad \dots 6$$

where, *ln* represents natural logarithm of the given variables; and the concentrations C*, Co and C_t are usually expressed in parts per million(ppm). The value of $k_L a_T$ thus obtained is to be converted to the value at a standard temperature of 20° C as $k_L a_{20}$, called the overall oxygen transfer coefficient, for the purpose of comparison of results, by the following equation (Manual of Practice for water pollution control, 1998):

$$k_L a_{20} = k_L a_T / \theta^{(T-20)} \qquad \qquad \dots 7$$

where, θ = 1.024 for pure water.

There are three basic techniques and several predictive equations for measuring the reaeration coefficient of a stream. These are described below:

(A). Dissolved Oxygen Balance Technique -- The dissolved oxygen balance approach was used by Streeter and Phelps (1925) in their classical study on the Ohio River. This technique consists of selecting a reach of stream, measuring all the sources and sinks of DO with the exception of reaeration, and determining by difference the reaeration needed to give the DO concentration

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observed at the downstream end of the reach. Under specialised conditions where many of the sources and sinks of DO are eliminated, the DO balance technique can be effectively used(Streeter and Phelps, 1925; Churchill, 1962; Issac, 1968).

(B). Distributed Equilibrium Technique – The distributed equilibrium technique was developed at the Water Pollution Research Laboratory and has been used extensively on several small streams in the United Kingdom(Zogorski and Faust, 1973). This technique consists of measuring the DO concentrations at the upstream and downstream ends of the reach at two different levels of DO concentration. These two levels are usually obtained by injecting sodium sulphite and a cobalt catalyst into the stream. If photosynthesis, respiration, reaeration coefficient, average velocity and saturation concentration is constant during the measurements, then the reaeration coefficient can be computed. The use of this technique is generally limited to small streams because it is necessary to artificially produce at least one of the DO deficits. Also, if photosynthesis is appreciable, then it may be necessary to do the experiments at night to eliminate this effect. Finally, the assumption required by the technique that respiration is independent of the DO concentration level has been questioned.

(C). Tracer Technique – The distributed equilibrium and DO balance techniques depends basically on the measurement of the DO concentrations in the reach of interest. The tracer technique, however, is unique in that it does not require the measurement of any of the sources and sinks of DO in the stream (Tsivoglou and Wallace, 1972). The basis of the technique is the observation that the ratio of the rate coefficient for desorption of a tracer gas from water to the rate coefficient for the absorption of oxygen by the same water is independent of temperature and flow conditions. Radioactive krypton is used as tracer gas, tritium is used to correct for dispersion and dilution, and Rhodamine-WT fluorescent dye is used to determine the time of sampling for the radioactive tracers.

(D). Predictive Equations – The measurement of the reacration coefficient by any of the three techniques requires considerable field and laboratory work, and in many water quality modelling studies, sufficient resources may not be available to permit measuring the reaeration coefficients. The alternative is to use one of the many predictive equations available in the literature.

Numerous equations employing depth, velocity and slope have been developed to estimate the stream reaeration coefficient. Table 1 summarises some of the most popularly used reaeration

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Table 1: Predictive Equations for Reaeration Coefficient (K_2)

Author(s)	K_2, base e (1/day at 20°C)
O'Connor and Dobbins (1958)	$K_2 = 3.90 V^{0.5} H^{-1.5}$
Churchill et al. (1962)	$K_2 = 5.010 V^{0.969} H^{-1.673}$
Krenkel and Orlob (1962)	$K_2 = 173(SV)^{0.404} H^{-0.66}$
Owens et al. (1964)	$K_2 = 5.35 V^{0.67} H^{-1.85}$
Langbein and Durum (1967)	$K_2 = 5.14 V H^{-1.33}$
Cadwallader and McDonnell (1969)	$K_2 = 186(SV)^{0.5} H^{-1}$
Thackston and Krenkel (1969)	$K_2 = 24.9(1 + F^{0.5}) u_* H^{-1}$
Parkhurst and Pomeroy (1972)	$K_2 = 23(1 + 0.17 F^2)(SV)^{0.375} H^{-1}$
Tsivoglou and Wallace (1972)	$K_2 = 31200 SV \qquad Q < 0.28 m^3/\text{sec}$ $K_2 = 15200 SV \qquad Q > 0.28 m^3/\text{sec}$
Smoot(1984)	$K_2 = 543 S^{0.6236} V^{0.5325} H^{-0.7258}$
Moog and Jirka(1998)	$K_2 = 1740 V^{0.46} S^{0.79} H^{0.74} \qquad s > 0.00$ $K_2 = 5.59 S^{0.16} H^{0.73} \qquad s < 0.00$
IHP(1998)	$K_2 = 2.148 V^{0.878} H^{-1.48}$
Jha, Ojha & Bhatia	$K_2 = 6.244 V^{0.558} H^{-0.234}$

V is the velocity in m/sec., H is the depth in m, S is the slope, F is the Froude number and u* is the friction velocity in m/sec.

coefficient expressions (K_2 values) for rivers including the equation developed in present study. All formulae for reaeration in Table 1 are the depth-averaged values and are in units of 1/day. All values of K_2 are base e, and are referenced to 20°C, unless otherwise specified.

1.1.3 Temperature

The temperature of water is one of the most important characteristics, which determines, to a considerable extent, the trends and tendencies of changes in its quality. Temperature is an important factor-affecting ion and phase equilibrium, influencing the rates of biochemical processes, which accompany the changes of concentration, and of content of organic and mineral substances. It is generally known that the rate of numerous chemical reactions including catalytic and enzymatic ones depend considerably on changes in temperature (on an average 2 to 3 times for every 10°C rise in temperature). Consequently, when discussing parameters such as sedimentation, mobilisation of un-dissolved substances, solution of gases and their escape from water into the atmosphere, the process of chemical and biochemical self purification, formation of secondary pollutants, and others, it is necessary to know the temperature of the water, air, and in some cases the bottom deposits.

The reaeration coefficient (K_2) and deoxygenation rate constant (K_1) depend on the ambient (water) temperature. The influence of temperature on reaeration is typically simulated using the following type of temperature dependence:

$$K_{a(T)} = K_{a(20^o C)}(1.047)^{(T-20)} \qquad \ldots 8$$

in which $K_{a(T)}$ is the value of rate coefficient at water temperature T°C, $K_{a(20^o C)}$ is the value of rate coefficient at water temperature T=20°C, and T= water temperature(T°C).

1.1.4 Photosynthesis and Respiration

The presence of aquatic plants in a water body can have a profound effect on the DO resources and the variability of the DO throughout a day or from day to day. All of the aquatic plant forms are important because of their ability to photosynthesise. The essence of the photosynthetic process centres about the chlorophyll-containing plants which can utilise radiant energy from the sun, convert water and carbon dioxide into glucose, and release oxygen. Because the photosynthetic

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process is dependent on solar radiant energy, the production of oxygen proceeds only during daylight hours. Concurrently with this production, however, the algae requires oxygen for respiration, which can be considered to proceed continuously. The two principal issues associated with the photosynthesis and respiration components of the DO problem are therefore (a) the degree to which the net effect of photosynthesis and respiration contributes to the average DO resources of the water body and (b) the expected diurnal variability in DO as a result of the presence of aquatic plants. There are three estimation methods of photosynthesis and respiration; (a) "Light and dark" bottle of chamber measurements of DO, (b) Estimation from observed chlorophyll levels, (c) Measurements of diurnal DO range (Thomann and Mueller, 1987).

1.2 Scope of the Study

Various numerical quality routing models are available that are capable of describing the waste transport and assimilation phenomena of the receiving waters throughout a river basin system viz. QUAL2EU, WASP5, HSPF, AGNPS etc. Simulation techniques offer an integrated and relatively sound approach for evaluating waste load abatement alternatives. Predictions of system behaviour based upon mathematical simulation techniques may be misleading, particularly, if the physical mechanisms involved are not accurately represented in the model. Further, even where the model does faithfully describe mechanisms in the prototype, poor results may be obtained where insufficient data are available to estimate rate coefficients.

Much of the work done in the water quality modelling field has been oriented toward improvement of models by incorporating better numerical solution techniques, an expanded complement of water quality constituents simulated, and toward realistic representations of modelled physical, chemical and biological phenomena. There is, however, a need for estimation of the rate constants and coefficients (reaeration and deoxygenation rate constants) needed in the model. No efforts have been made in India to estimate the rate constants and the model variables have been taken from the published literature.

In the year 1992-93 and 1994-95 water quality surveys were carried out by the National Institute of Hydrology (Jain et al. 1992 and Ghosh, 1995) to monitor various wastewater

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contaminants between Malira Bridge and Mansurpur Bridge of the river Kali (Fig.2). QUAL-2E model was also used to predict the water quality variables in river Kali. Infact, the surveys were carried out to study the effect of municipal and industrial wastes from Muzaffarnagar only. Secondly, sampling were conducted only for two reaches of the stream (Malira Bridge (u/s) and Mansurpur (d/s) of Muzaffarnagar town) and incoming point sources.

In the present study, exhaustive field surveys and regular monthly monitoring of water quality were carried out at sixteen river locations (from the origin of the river to its confluence with the river Hindon) and six point sources, covering a length of 102 kms (Fig.3) to fulfil the following objectives:

1. Collect in-stream data of DO, BOD, photosynthesis, respiration and temperature (used in the traditional BOD-DO model) to estimate reaeration and deoxygenation rate constant for different reaches of river Kali (a tributary of river Hindon) as the range of rate constants depends on many hydrological and hydraulic parameters and vary from stream to stream.

2. Develop an empirical equation based on hydraulic parameters and estimated reaeration coefficients to compute the reaeration coefficient for Kali River to avoid detailed field investigations. Numerous equations developed earlier by various workers employing depth, velocity and slope to estimate the stream reaeration coefficient have also been evaluated using statistics based on differential and multiplicative errors.

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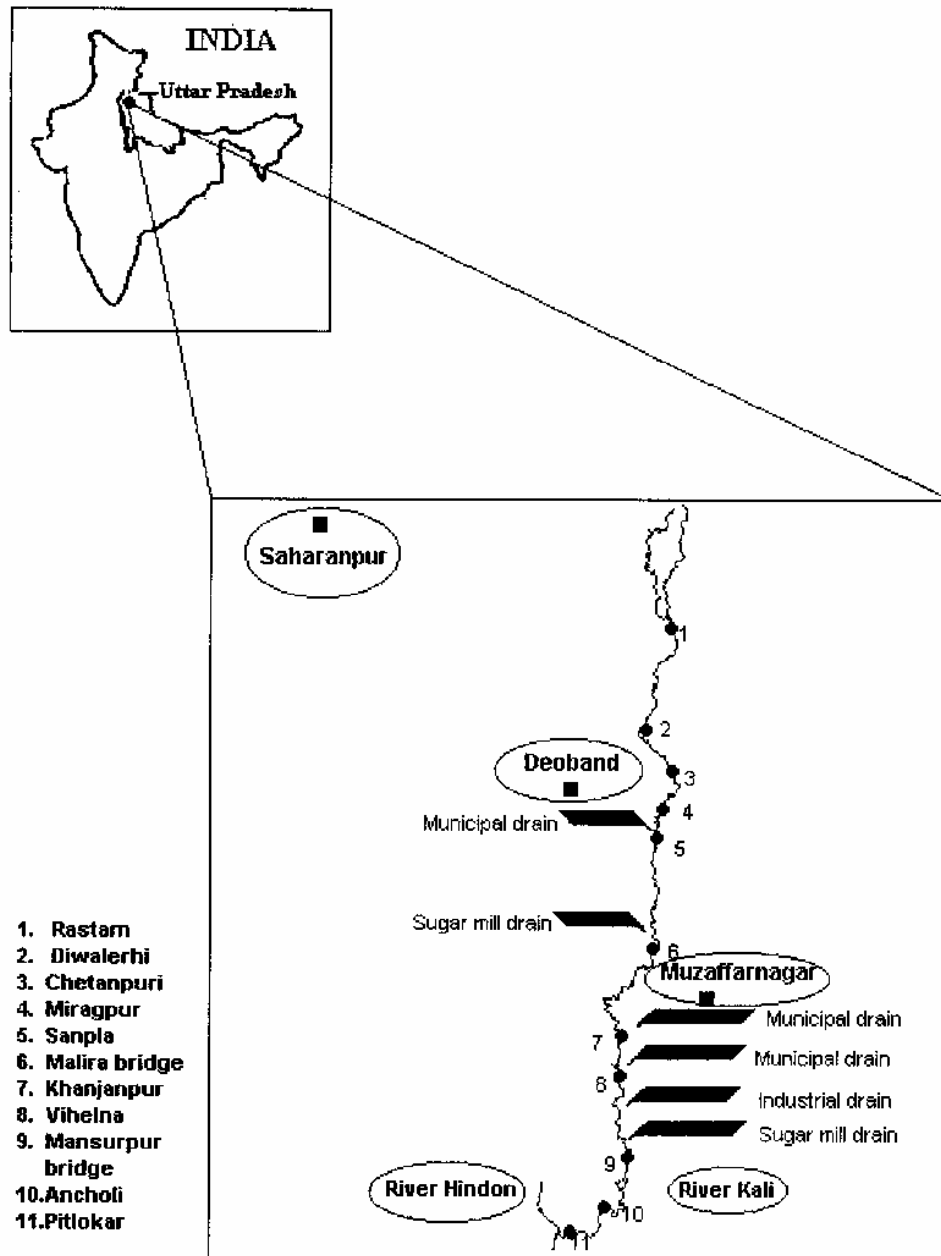
Fig.2: Location map of Kali River

River Kali

Present Survey

Rastam

Diwaleri

Chetanpuri

Miragpur

Sanpla(u/s)

Sanpla(d/s)

Malira bridge(u/s)

Earlier Survey

Malira bridge(d/s)

Khanjanpur(u/s)

Khanjanpur(d/s)

Vihelna(u/s)

Vihelna(d/s)

Mansurpur bridge(u/s)

Mansurpur bridge(d/s)

Ancholi

Pitlokar

Municipal drain

Suger Mill drain

Municipal drain

Municipal drain

Industrial drain

Sugar mill drain

Confluence of Kali and Hindon rivers

Fig.3: General Plan of the Sampling Points in Kali River

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2.0 THE STUDY AREA

The river Kali is an important left bank tributary of river Hindon originating near Saharanpur district in western Uttar Pradesh, India. The river traverses a course of 125 kms before meeting the river Hindon with the total catchment area of about 750 sq.kms. The study area is a part of Yamuna basin in the Indogangetic Plains, composed of Pleistocene and subrecent alluvium and 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 monsoon period (June to September). The basin area lies between the elevations from 276 to 221 above m.s.l. with agriculture as the major land use. The soils of the area are loam to silty loam and are normally free from carbonates.

Excessive disposal of wastewater contaminants beyond the limit of ablution capacity of the river water body pollutes the water and causes serious problems to the fish life, aquatic biota, human health and the environment. Due to urbanisation, inception of industries, use of chemicals and pesticides for agriculture, and increase in population, the disposal of wastewater effluent to the river Kali have been increasing exponentially resulting in sharp deterioration of river water quality. To decontaminate, intercept, divert and treat 722 mld of wastewater flowing to the river Yamuna and its tributaries including Kali, Ganga Action Plan Phase II (GAP-II) has been initiated in the year 1992 and is proposed to be commissioned before March'2000.

The main sources which contribute to pollution in the river include municipal waste of Deoband city, sugar mill drain of Rohana near Deoband city, municipal waste of Muzaffarnagar city, waste from a variety of industries (such as steel, rubber, ceramic, chemical, plastic, dairy, pulp and paper, and laundries), Mansurpur sugar mill and distillery waste, and return flow from agricultural land. The river Kali receives 32 MLD of untreated municipal, industrial and sugar mill effluent from Muzaffarnagar City every day (Yamuna pollution control unit, UP Jal Nigam, Muzaffarnagar, 1993). The water resources of this region are utilised for the disposal of industrial wastes of more than 20 different industries (Verma et al., 1974). Agriculture waste is another factor contributing to pollution of the river water. The river quality has been continuously degrading due to ignorance in control and management of water quality aspects. The river has a significant socio-economic value to nearby areas e.g. the river water is used for washing clothes, recreation of

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domestic animals, as a carrier for municipal and industrial wastes, and in many cases water is drawn for agriculture uses as well.

In the present study, twenty-two sampling points in a stretch of 102 kms were selected for comprehensive water quality monitoring of river Kali as shown in Fig.3. All the sampling points significantly represent the possible sources of pollution due to point or non-point sources. Also, the points are well selected to estimate deoxygenation and reaeration rate constants. The briefs of sampling points are as follows:

- Rastam is the first point of sampling at about 20 kms downstream of the origin of the river Kali. The pollution of this reach is mainly due to diffused and distributed sources.

- Diwaleri is the second point of sampling 4 kms downstream of first point. The pollution of this reach is mainly due to diffused and distributed sources.

- Chetanpuri is the third point of sampling 4.15 kms downstream of the second point. The pollution of this reach is mainly due to diffused and distributed sources.

- Miragpur is the fourth point of sampling 2.2 kms downstream of the third point. The pollution of this reach is due to point source pollution from Miragpur village and nearby agriculture area.

- Deoband drain is the fifth point of sampling 4.0 kms downstream of fourth point. It is the main source of pollution that carries municipal waste.

- Sanpla (u/s) is the sixth point of sampling 1.1 kms downstream of the fifth point. The pollution above the reach is mainly due to main drain of Deoband town.

- Sanpla (d/s) is the seventh point of sampling 20 kms downstream of the sixth point. The pollution of this reach is mainly due to diffused sources.

- Rohana sugar mill is the eighth point of sampling 0.10 kms downstream of seventh point. The pollution is mainly due to disposal of sugar mill effluent into the river Kali.

- Malira Bridge (u/s) is the ninth point of sampling 0.65 kms downstream of the eighth point. The pollution above reach is mainly due to discharge from Rohana sugar mills and some distributed sources of pollution.

- Malira Bridge (d/s) is the tenth point of sampling 12.65 kms downstream of the ninth point. The pollution of this reach is mainly due to diffused sources of pollution.

- Niyajupura municipal drain is the eleventh point of sampling 0.10 kms downstream of tenth point. It is one of the main sources of pollution that carries municipal waste.

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- Khanjanpur Bridge (u/s) is the twelfth point of sampling 0.40 kms downstream of eleventh point. The pollution above the reach is mainly due to Niyajupura municipal drain.

- Khanjanpur Bridge (d/s) is the thirteenth point of sampling 0.70 kms downstream of twelfth point. The pollution of this reach is mainly due to Niyajupura municipal drain.

- Muzaffarnagar drain is the fourteenth point of sampling 0.10 kms downstream of thirteenth point. It is the main municipal drain that carries municipal waste.

- Vihelna (u/s) is the fifteenth point of sampling 0.50 kms downstream of eleventh point. The pollution of this reach is mainly due to Muzaffarnagar municipal drain.

- Vihelna (d/s) is the sixteenth point of sampling 8.50 kms downstream of fifteenth point. The pollution of this reach is mainly due to Muzaffarnagar municipal drain.

- Begharajpur Industrial drain is the seventeenth point of sampling 8.75 kms downstream of sixteenth point. It is the main Industrial drain which carries mixed waste from variety of industries (such as steel, rubber, ceramic, chemical, plastic, dairy, pulp and paper, and laundries) and municipal areas.

- Mansurpur sugar mill is the eighteenth point of sampling 0.50 kms downstream of the seventeenth point. It is the main sugar mill drain that carries sugar mill wastes with it.

- Mansurpur Bridge (u/s) is the nineteenth point of sampling 0.75 kms downstream of eighteenth point. The pollution of this reach is mainly due to industrial and sugar mill drains and some distributed sources of pollution.

- Mansurpur Bridge (d/s) is the twentieth point of sampling 1.50 kms downstream of nineteenth point. The pollution of this reach is mainly due to industrial and sugar mill drains and some distributed sources of pollution.

- Ancholi is the twenty-first point of sampling 22.0 kms downstream of twentieth point. The pollution of this reach is mainly due to distributed and diffused sources of pollution.

- Pitlokar is the twenty-second point of sampling 9.9 kms downstream of twenty-first point. The pollution of this reach is mainly due to distributed and diffused sources of pollution.

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3.0 METHODOLOGY

3.1 Physio-Chemical Parameters

Samples of the river water and effluent were collected from sixteen river sampling points and six point sources effluent points using Hydro-Bios standard water sampler over a period from March'99-January'99 by the dip/grab sampling method. All the samples were collected at about 15 cm depth from three points across a location of the river (1/3, 1/2, and 2/3), and stored in pre-cleaned polythene bottles. The effluent samples from six out falls were collected from the middle of the drains. In the Kali River the flow velocity is very low and thus the travel time of flow from one reach to another is more. Considering these aspects, it was difficult to cover the complete sampling over all the points of the Kali River in one day. Due to high travel time of river water, the sampling was carried continuously three days in one month. The complete survey was done continuously in three days. Also, at every river point, the sampling was done three times (morning, afternoon and evening) in one day to study the effect of temperature on reaeration.

The data collected from river reaches and point sources are given in Table 2. Some parameters, such as temperature, pH, turbidity, area, velocity and electrical conductivity were measured in the field by means of portable meters (WTW, Germany) and current meter. For other parameters, samples were preserved by adding appropriate reagent (APHA, 1985). The samples so preserved were brought to the laboratory, in sampling kits maintained at $4^\circ C$, for detailed chemical analysis of DO and BOD.

Physio-chemical analyses were conducted following standard methods (APHA, 1985). DO determination was based on Winkler method with the addition of divalen manganese solution and alkali-iodide-azide reagent. BOD5 were obtained by incubating the un-preserved samples for five days. Total dissolved solids (TDS) and suspended solids were measured by standard procedure. The flows in different reaches of the stream and point sources were determined by area-velocity method.

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Table 2: Data collected from reaches of Kali River

S.No.	Water Quality Variables collected from	
	River Reaches	Point Sources
1.	Dissolved oxygen	Biochemical oxygen demand
2.	Biochemical oxygen demand	Temperature
3.	Photosynthesis	Total dissolved solids
4.	Respiration by plants	pH
5.	Temperature	Total suspended solids
6.	Total dissolved solids	Turbidity
7.	pH	Colour
8.	Total suspended solids	Odour
9.	Turbidity	Velocity
10.	Colour	Cross-sectional area
11.	Odour	
12.	Velocity	
13.	Cross-sectional area	

3.2 Deoxygenation rate constants (K_1)

The deoxygenation rate constant, K_1, was determined from the water quality data and from estimated travel times obtained by field surveys during March'99 to January-2000. The BOD_5 values were determined by Standard method of incubation. The BOD_5 obtained at different reaches were plotted on log scale and the travel time was plotted on normal scale. The slope of the line gives the values of deoxygenation coefficient (K_1).

3.3 Reaeration Coefficient (K_2)

The reaeration coefficient, K_2, was computed using two techniques, namely; (i) dissolved oxygen balance technique (DOBT), and (ii) most commonly used predictive equations (PEs) including development of one predictive equation for present study.

3.3.1 Dissolved oxygen balance technique (DOBT)

The dissolved oygen balance technique (DOBT) is the traditional technique developed by Streeter and Phelphs (1925) and is based on the mass balance of oxygen in a river reach. In the present study, all the parameters used in the equation as given below have been determined either in the field or in the laboratory except reaeration coefficient. The following equation has been used to determine reaeration coefficient (K_2) by trial and error method.

$$D = \frac{K_1 L_0}{K_2 - K_1}(e^{-K_1 t} - e^{-K_2 t}) + D_0 e^{-K_2 t} \qquad \ldots 9$$

in which, D= Dissolved oxygen deficit at time t (mg/l), K_1= Deoxygenation rate constants (1/day), t= travel time (days), L_0= Initial BOD (mg/l), D_0= Initial DO deficit (mg/l), K_2= reaeration coefficient (1/day).

All the parameters required for DOBT were measured and monitored every month three times in a day. A total of 270 values of reaeration coefficient (K_2) were obtained by sampling from different reaches during March, 1999 to January 2000.

3.3.2 Predictive Equations (PEs)

The K_2 is frequently determined by predictive equations employing mean stream parameters- generally depth H, velocity V and slope S. Dozens of such equations have been developed and applied. While this abundance reflects a great deal of effort, it also reflects the lack of an accurate general formula. This lack would appear to arise from the tremendous variations in flow found both within individual streams and between different channel types, as well as from unaccounted variables such as wind shear and surface films.

In this study most commonly used predictive equations (PEs) as mentioned in Table 1 have been used to estimate the reaeration coefficient (K_2) at different reaches of river Kali. A total of 270 values of reaeration coefficient were obtained by all the predictive equations which were compared with the reaeration coefficients (K_2) estimated by dissolved oxygen balance technique (DOBT). A new predictive equation has also been developed for river Kali for the water temperature of 20° C. In this process, the reaeration coefficients were determined using "Least square approach" to calculate a straight line that best fits the data, and returns an array that describes the line. The reaeration coefficient estimated by DOBT, velocity and depth data were used to determine the best-

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fit predictive equation. The slope of the Kali River is very mild and is not an important factor in the development of predictive equation. The temperature corrections can be made using equation 7 for a given water temperature to estimate reaeration coefficient (K_2).

3.4 Photosynthesis and respiration

The "Light and dark" bottle method was used to determine photosynthesis and respiration rates. The method uses the concept that exposing the aquatic plants to the natural light conditions and measuring the change (increase) in DO is an estimate of photosynthesis gross DO production minus the DO utilised in respiration, that is, the net production of DO. The maintenance of a parcel of water in a "dark" environment will provide an estimate of the total DO respiration, since the plants are not photosynthesising. The addition of two rates from the light and dark bottles will then be a measure of the gross production of DO.

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 water and preserved for DO measurement. After six hour, six sets of dark and light bottle were ready to study the photosynthesis (from light bottle) and respiration (from dark bottle) phenomena. This experiment was limited to sunny days, as it could not be conducted in cloudy days and during winters when the river water temperatures were low.

3.5 Performance Evaluation

The reaeration coefficient (K_2) computed by predictive equations needs to be evaluated. In the present study, two evaluation criteria have been followed; (a) computation of correlation coefficient; and (b) error estimation.

3.5.1 Correlation coefficient estimation

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. Correlation analysis is also used as a "Goodness of Fit" test by determining how closely a

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regression equation fits the sample points. 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:

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{B\sqrt{[n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2][n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2]}} \qquad \dots 10$$

The correlation coefficient r can be tested for the level of significance by the Student's t-test. Because r can be either positive or negative, the sign of the resulting test values is ignored. The t test form is:

$$t_{test} = r\frac{n-2}{1-r^2} \qquad \dots 11$$

in which, r is the correlation coefficient, and n is the total no. of samples.

3.5.2 Error Estimation

To evaluate the predictive peroformance of reaeration equations statistics based on differential and multiplicative error equations such as normalized mean error (NME), standard error (SE) or mean multiplicative error (MME) have been used.

$$NME = \frac{100\%}{N} \sum_{i=1}^{N} \left(\frac{K_P - K_M}{K_M} \right)_i \qquad \dots 12$$

$$SE = \left(\sum_{i=1}^{N} \frac{(K_P - K_M)^2}{N} \right)^{1/2} \qquad \dots 13$$

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where N is the number of reaeration measurements; K_P and K_M are predicted and measured value. In the SE, the error ($K_P - K_M$), produces a small error in large K_2 values, which would be relatively large at small K_2. Also, it has been criticised (Wilson and Macleod, 1974) for the squared error, which causes it to focus on eliminating the largest errors. Because outliers and large errors (> 100%) are very common, in reaeration prediction, this criticism is warranted, The SE's over-sensitivity and lack of scaling is eliminated by the NME- at the cost of measuring precision, because positive and negative errors cancel. Probably the greatest defect in both is that they are based on the differential error ($K_P - K_M$). Given the large errors common in reaeration prediction, differentials create unintended distortions. Although overestimates ($K_P ->K_M$) are unbounded and often well over 100 %, underestimates are limited to 100 %. As a consequence, the distribution of residuals is skewed.

Instead of differential errors, the mean multiplicative error(MME), that is K_P/K_M, over comes this defect and offers other advantages, including identical results for both reaeration and gas transfer coefficients and less sensitivity to extreme errors. It is equal to the geometric mean of the factors, greater than unity, by which the estimates would have to be multiplied or divided to equal the corresponding measurements.

Because ln (K_P)-ln (K_M) = ln (K_P/K_M), differential error in ln (K) reflects multiplicative errors in K. They provide a better basis for assessing the impact of inaccuracies in predicting reaeration coefficients. The mean multiplicative error may be defined as:

$$MME = \exp\left[\frac{\sum_{i=1}^{N}\left|\ln(K_P/K_M)_i\right|}{N}\right]$$ ...14

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4.0 RESULTS AND DISCUSSION

4.1 Dissolved Oxygen and Biochemical Oxygen Demand

The variations of DO and BOD in Kali River during different months are shown in Fig.4. As can be seen from the figure, the critical (lowest) dissolved-oxygen concentrations occur at a distance of about 50 km. onwards. The DO reaches upto zero due to the disposal of municipal, industrial and sugar mill wastes from Muzaffarnagar Town, which are being discharged without prior treatment into the river beyond its assimilative capacity. Consequently, anaerobic condition occurs for the river length of nearly 10 kms. However, before disposal of any wastes into a river, it is essential to know the self-purification capacity of the river at different reaches due to deoxygenation and reaeration. Figure 4 also indicates that the discharge from municipal, industrial and sugar mill wastes dominates the system to such an extent that the effects of reaeration are almost negligible. The BOD is also found to be very high during lean flow period.

4.2 Reaeration Coefficient (K_2)

As explained earlier, reaeration of a stream is the physical absorption of oxygen from the atmosphere, and the rate coefficient describing this process is the reaeration coefficient, K_2. Because the reaeration coefficient is one of the parameters necessary for water quality modelling, it is essential that techniques be available for measuring or predicting this coefficient with an acceptable degree of accuracy.

In the present study, two approaches namely, Dissolved oxygen balance technique (DOBT) of Streeter and Phelps, and most commonly used Predictive Equations (PEs) were applied to determine the reaeration coefficient (K_2) in different reaches of Kali River. All the water quality variables needed for DOBT were monitored. It has been found that photosynthesis and respiration have negligible effect due to absence of algae in the river. The "light and dark" bottle approach was used for DO measurement due to photosynthesis and respiration and no variation was found in eight hours (day time) of experiments carried out at different reaches of the stream several times. The DO, BOD, temperature and travel times are the other major factors affecting the reaeration

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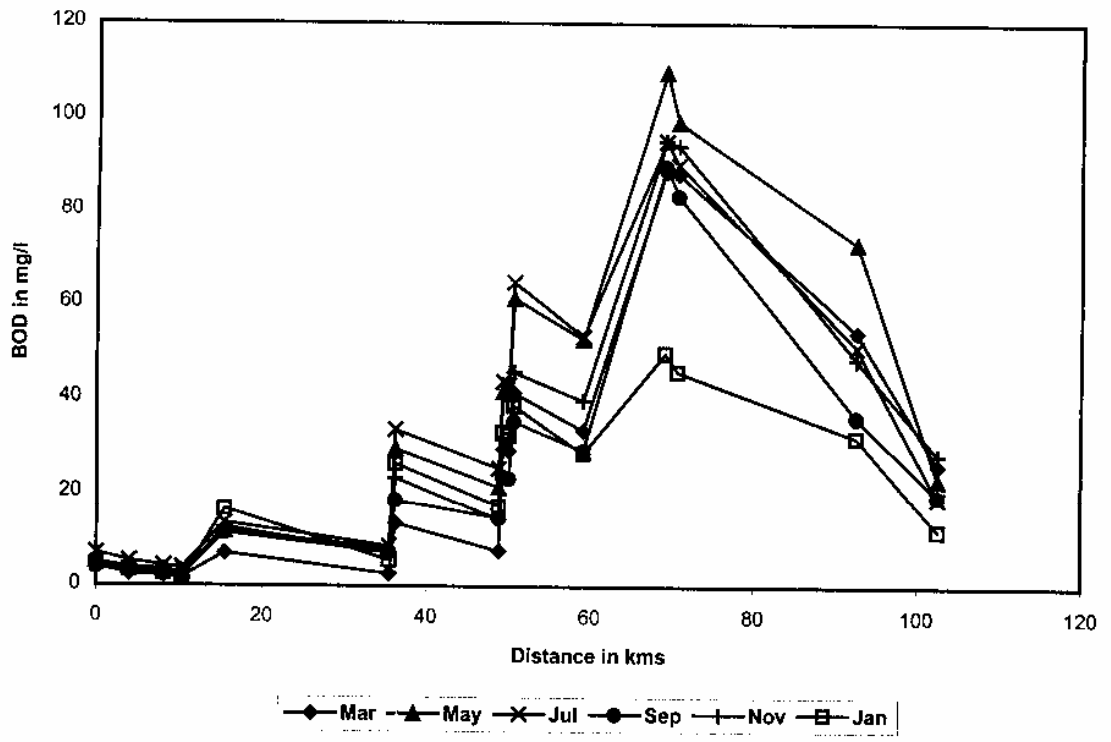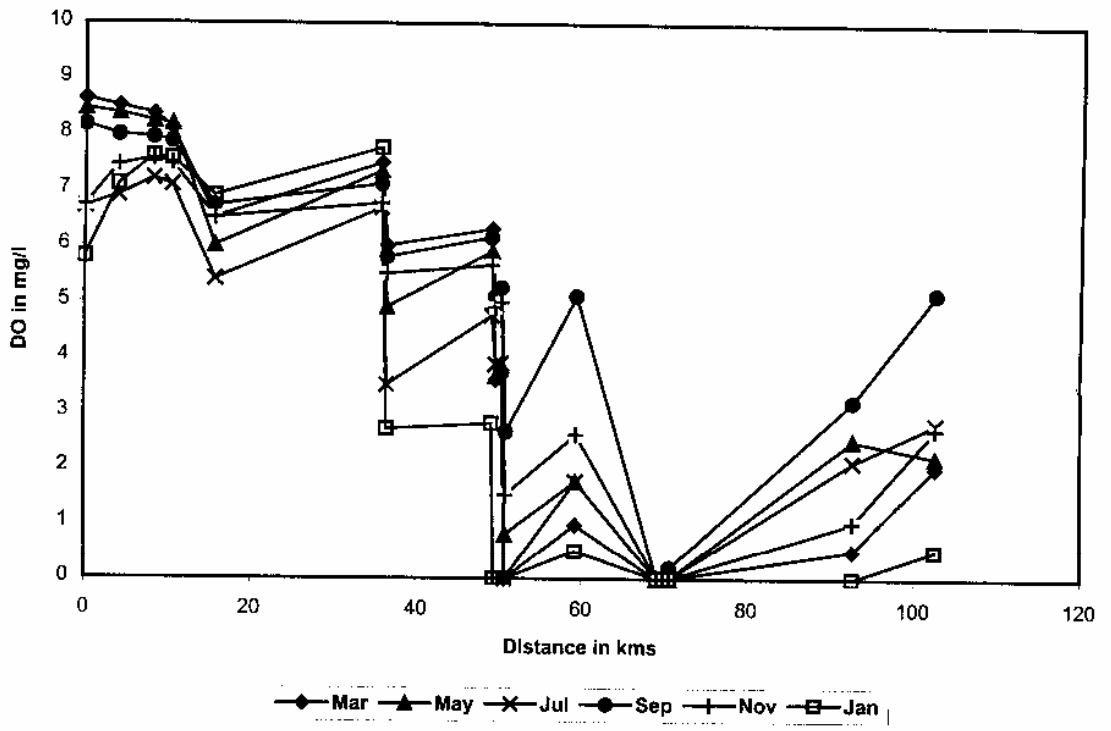
FIG.4: DO AND BOD VARIATION IN RIVER KALI

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coefficient (K2) and were monitored regularly. The values of reaeration coefficient (K_2) estimated by DOBT are given in Table 3. The best-fit values of K_2 in equation 1 were determined by Newton Raphson iteration technique for all the 270 field data.

The results obtained using most commonly used PEs (as given in Table 1) are shown in Table 3. Comparisons of results obtained by two methods were made and the performances of PEs were evaluated using "correlation coefficient" or "goodness of fit" and "differential and multiplicative errors". Three well known methods namely; Standard Error (SE), Normal Mean Error (NME) and Mean Multiplicative Error (MME) were used to estimate the differential and mean errors. Table 4 provide the correlation coefficient, SE, NME and MME of PEs with DOBT. The results do not show good correlation and errors are found to be high. The PEs developed by Smoot (1988) has been found to be reasonably good among other equations.

It has been observed from satellite data of Kali River and its field survey, that in the upper catchment area river is highly meandering in nature and the meandering pattern reduces towards downstream with the increase in width and depth of the stream. As the reaeration coefficient is a function of turbulence, the reaeration coefficient in the upper reaches is found to be higher as compared to lower reaches. The flow is found to be sub-critical in nature. In the exhaustive survey for determination of reaeration coefficient (K_2) using DOBT, it was observed that the reaeration coefficient depends on hydraulic parameters such as velocity, depth, slope etc. Thus, based on velocity (V) and depth (H), a predictive equation was developed using the "least squares" method to arrive at a straight line that best fits the data, and returns an array that describes the line. The slope of the river is very mild and is not very important for Kali River. The equation developed is as follows:

$$K_2 = 6.244 V^{0.558} H^{-0.234} \qquad \qquad \dots 15$$

$$(r^2 = 0.965)$$

in which V is the velocity in m/sec and H is the depth of flow in m.

The comparisons of results using equation 15 with DOBT are illustrated in Figure 5. As can be seen from the figure that the results obtained using equation 10 show a good agreement with

Table 3: Reaeration Coefficient Estimated by DOBT and PEs

Method	Station	Reaeration coefficient for 20oC								
		March	April	May	July	Aug	Sept	Nov	Dec	Jan
DOBT	Rastam to Diwaleri	7.1	6.08	6.06	4.37	4.17	6.51	7.58	4.43	4.94
	Diwaleri to Chetanpuri	6.6	5.67	5.19	4.89	3.87	6.33	6.1	4.45	3.04
	Chetanpuri to Miragpur	3.7	4.92	4.99	5.54	4.43	5.32	4.85	2.89	4.22
	Sanpla (u/s) to Sanpla (d/s)	3.16	5.88	5.77	5.76	4.27	5.96	5.73	2.59	4.86
	Malira (u/s) to Malira (d/s)	3.3	5.1	5.83	4.38	3.81	5.13	4.94	1.87	2.45
	Khanjanpur (u/s) to Khanjanpur (d/s)	2.28	3.81	4.79	3.98	4	4.91	4.33	2.47	2.81
	Vihelna (u/s) to Vihelna (d/s)	2.06	3.45	3.47	3.9	4.2	5.16	3.1	2.8	3.12
	Mansurpur (u/s) to Mansurpur (d/s)	3.58	4.8	4.5	4.04	4.42	4.9	4.1	5.31	4.05
	Mansurpur (d/s) to Ancholi	3	3.63	4.79	4.16	4.04	5.23	3.66	3.5	3.35
	Ancholi to Pitlokar	3.1	2.9	4.06	3.42	4.06	5.11	3.22	3	3.17
O'Conner & Dobbins(1958)	Rastam to Diwaleri	33.88	32.7	13.5	39.1	9.47	22.25	143	18.13	32.82
	Diwaleri to Chetanpuri	43.51	36.56	9.63	35	5.66	23.18	79	12.56	26.1
	Chetanpuri to Miragpur	25.79	22.36	8.17	27.6	6.28	16.65	37.4	8.32	49.92
	Sanpla (u/s) to Sanpla (d/s)	7.39	10.11	8.84	8.91	4.61	9.61	12.4	4.54	7.14
	Malira (u/s) to Malira (d/s)	4.2	5.65	5.22	5.23	4.29	7.29	6.63	3.99	5.84
	Khanjanpur (u/s) to Khanjanpur (d/s)	5.01	6.8	7.87	5.21	3.93	7.87	6.63	4.57	6.89
	Vihelna (u/s) to Vihelna (d/s)	5.02	5.84	6.94	5.32	3.67	6.85	7.64	3.7	5.73
	Mansurpur (u/s) to Mansurpur (d/s)	4.48	6.24	6.34	6.69	3.73	6.53	7.19	3.88	8.27
	Mansurpur (d/s) to Ancholi	4.41	5.51	5.28	5.51	2.93	5.3	6.53	3.47	8.93
	Ancholi to Pitlokar	5.07	4.84	4.94	4.48	2.84	5.07	6.74	3.05	7.71
Churchill et al.(1962)	Rastam to Diwaleri	39.84	37.2	14.1	42.1	8.75	25.16	202	18.68	32.39
	Diwaleri to Chetanpuri	51.66	39.94	9.32	36.7	5.15	25.85	99.5	11.85	22.39
	Chetanpuri to Miragpur	25.11	24.1	7.84	30.5	6.3	17.34	38.5	6.6	56.53
	Sanpla (u/s) to Sanpla (d/s)	5.59	10.24	9.38	8.27	4.22	9.87	12.5	2.93	4.75
	Malira (u/s) to Malira (d/s)	3.07	4.8	4.51	4.62	4.22	7.87	5.52	2.91	4.65
	Khanjanpur (u/s) to Khanjanpur (d/s)	3.81	6.26	7.89	4.38	3.92	7.89	5.81	3.93	6.42
	Vihelna (u/s) to Vihelna (d/s)	3.56	4.65	6.18	4.38	3.28	5.87	6.89	2.75	4.49
	Mansurpur (u/s) to Mansurpur (d/s)	3.14	5.3	5.46	6.21	3.43	5.78	6.13	2.87	8.03
	Mansurpur (d/s) to Ancholi	3.45	4.78	4.51	4.9	2.6	4.63	5.64	2.75	9.56
	Ancholi to Pitlokar	4.26	4.14	4.14	3.71	2.41	4.26	5.84	2.47	8.38

Method	Reach									
Krenkel and Orlob(1962)	Rastam to Diwaleri	14.53	14.12	9.65	14.8	7.95	12.13	27.6	10.74	13.27
	Diwaleri to Chetanpuri	16.08	14.48	8.17	14	6.47	12.25	20.8	8.96	11.4
	Chetanpuri to Miragpur	12.01	11.89	7.64	13	7.03	10.45	14.2	7.06	16.61
	Sanpla (u/s) to Sanpla (d/s)	6.6	8.5	8.24	7.78	5.99	8.38	9.19	5.09	6.15
	Malira (u/s) to Malira (d/s)	5.22	6.26	6.12	6.19	6.01	7.7	6.61	5.11	6.17
	Khanjanpur (u/s) to Khanjanpur (d/s)	5.69	6.98	7.68	6.05	5.85	7.68	6.76	5.8	7.05
	Vihelna (u/s) to Vihelna (d/s)	5.52	6.17	6.93	6.03	5.42	6.78	7.24	5.01	6.08
	Mansurpur (u/s) to Mansurpur (d/s)	5.25	6.51	6.59	6.96	5.52	6.75	6.89	5.09	7.71
	Mansurpur (d/s) to Ancholi	5.49	6.26	6.12	6.33	4.95	6.19	6.68	5.03	8.3
	Ancholi to Pitlokar	5.98	5.92	5.91	5.66	4.8	5.98	6.77	4.83	7.89
Owens(1964)	Rastam to Diwaleri	73.66	70.25	23.6	86.8	15.1	43.92	435	33.81	69.27
	Diwaleri to Chetanpuri	100.04	80.07	15.5	75.5	8.05	46.09	208	21.38	51.46
	Chetanpuri to Miragpur	51.56	43.91	12.7	56.9	9.26	30.51	81.6	12.66	117.6
	Sanpla (u/s) to Sanpla (d/s)	10.89	16.56	14.1	14	6.28	15.6	21.3	5.89	10.27
	Malira (u/s) to Malira (d/s)	5.44	7.96	7.25	7.29	5.8	11.21	9.65	5.12	8.22
	Khanjanpur (u/s) to Khanjanpur (d/s)	6.78	10.09	12.2	7.2	5.23	12.18	9.72	6.16	10.26
	Vihelna (u/s) to Vihelna (d/s)	6.74	8.22	10.3	7.38	4.74	10.08	11.6	4.67	8.02
	Mansurpur (u/s) to Mansurpur (d/s)	5.86	8.99	9.18	9.89	4.85	9.55	10.7	4.95	12.9
	Mansurpur (d/s) to Ancholi	5.83	7.74	7.35	7.77	3.6	7.39	9.53	4.35	14.33
	Ancholi to Pitlokar	6.97	6.61	6.76	5.98	3.45	6.97	9.9	3.74	12.02
Langbein and Durum(1967)	Rastam to Diwaleri	22.13	20.62	9.66	21.8	6.29	15.43	81.2	11.72	17.06
	Diwaleri to Chetanpuri	26.92	21.17	6.78	19.4	4.23	15.61	45.1	7.95	11.94
	Chetanpuri to Miragpur	14.04	14.52	5.95	17.5	5.21	11.18	19.9	4.65	27.91
	Sanpla (u/s) to Sanpla (d/s)	4	7.48	7.22	6.06	3.68	7.33	8.63	2.27	3.28
	Malira (u/s) to Malira (d/s)	2.53	3.85	3.71	3.84	3.84	6.42	4.21	2.43	3.62
	Khanjanpur (u/s) to Khanjanpur (d/s)	3.03	4.91	6.14	3.58	3.67	6.14	4.51	3.35	5.04
	Vihelna (u/s) to Vihelna (d/s)	2.77	3.62	4.78	3.53	3	4.49	5.2	2.36	3.49
	Mansurpur (u/s) to Mansurpur (d/s)	2.5	4.14	4.26	4.91	3.16	4.52	4.61	2.42	6.1
	Mansurpur (d/s) to Ancholi	2.88	3.89	3.69	4.02	2.53	3.82	4.38	2.45	7.36
	Ancholi to Pitlokar	3.5	3.47	3.42	3.14	2.33	3.5	4.5	2.3	6.75

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	11.87	11.46	6.4	12.5	4.89	9	31.2	7.64	10.84
Cadwallader and McDonnell(1969)									
Rastam to Diwaleri	11.87	11.46	6.4	12.5	4.89	9	31.2	7.64	10.84
Diwaleri to Chetanpuri	13.92	12.08	5.03	11.6	3.53	9.19	20.6	5.87	8.89
Chetanpuri to Miragpur	9.29	8.86	4.53	10.2	3.92	7.28	12	4.24	14.87
Sanpla (u/s) to Sanpla (d/s)	3.86	5.28	4.95	4.71	3.12	5.15	5.99	2.68	3.59
Malira (u/s) to Malira (d/s)	2.68	3.43	3.29	3.32	3.07	4.42	3.75	2.6	3.41
Khanjanpur (u/s) to Khanjanpur (d/s)	3.04	3.97	4.5	3.25	2.92	4.5	3.83	3.02	4.02
Vihelna (u/s) to Vihelna (d/s)	2.96	3.41	3.97	3.26	2.68	3.88	4.24	2.5	3.35
Mansurpur (u/s) to Mansurpur (d/s)	2.75	3.64	3.7	3.94	2.74	3.81	3.99	2.57	4.58
Mansurpur (d/s) to Ancholi	2.84	3.4	3.3	3.44	2.32	3.33	3.78	2.46	5
Ancholi to Pitlokar	3.19	3.12	3.14	2.94	2.24	3.19	3.86	2.3	4.59
Thackston and Krenkel(1969)									
Rastam to Diwaleri	5.02	4.95	3.5	5.33	3.08	4.25	8.91	3.94	5
Diwaleri to Chetanpuri	5.54	5.19	3.08	5.11	2.52	4.32	7.02	3.43	4.63
Chetanpuri to Miragpur	4.55	4.27	2.89	4.63	2.6	3.81	5.25	2.98	5.86
Sanpla (u/s) to Sanpla (d/s)	4.48	4.18	3.52	4.71	2.61	4.06	4.76	2.88	4.72
Malira (u/s) to Malira (d/s)	2.86	3.13	2.96	3	2.32	3.07	3.4	2.43	2.88
Khanjanpur (u/s) to Khanjanpur (d/s)	2.27	2.56	2.43	2.45	2.34	2.64	2.8	2.27	2.55
Vihelna (u/s) to Vihelna (d/s)	2.3	2.53	2.45	2.45	2.24	2.74	2.71	2.26	2.59
Mansurpur (u/s) to Mansurpur (d/s)	2.39	2.65	2.69	2.45	2.15	2.82	2.67	2.28	2.66
Mansurpur (d/s) to Ancholi	2.46	2.7	2.84	2.46	2.16	2.84	2.69	2.33	2.71
Ancholi to Pitlokar	2.43	2.65	2.79	2.45	2.12	2.78	2.7	2.29	2.65
Parkhurst and Pomeroy(1972)									
Rastam to Diwaleri	4.57	4.44	2.45	4.95	1.91	3.44	12.3	2.97	4.35
Diwaleri to Chetanpuri	5.4	4.74	1.94	4.58	1.36	3.53	8.09	2.3	3.68
Chetanpuri to Miragpur	3.71	3.43	1.74	3.95	1.47	2.81	4.77	1.72	5.86
Sanpla (u/s) to Sanpla (d/s)	1.59	2.02	1.86	1.84	1.19	1.95	2.31	1.13	1.53
Malira (u/s) to Malira (d/s)	1.09	1.35	1.28	1.29	1.14	1.64	1.49	1.05	1.37
Khanjanpur (u/s) to Khanjanpur (d/s)	1.23	1.54	1.71	1.~3	1.08	1.71	1.5	1.17	1.55
Vihelna (u/s) to Vihelna (d/s)	1.22	1.37	1.55	1.29	1.02	1.53	1.65	1	1.35
Mansurpur (u/s) to Mansurpur (d/s)	1.13	1.44	1.45	1.52	1.03	1.49	1.58	1.04	1.76
Mansurpur (d/s) to Ancholi	1.13	1.33	1.29	1.33	0.88	1.3	1.48	0.97	1.87
Ancholi to Pitlokar	1.25	1.22	1.23	1.15	0.86	1.25	1.52	0.89	1.7

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Method	Reach									
Tsivoglou and Wallace(1972)	Rastam to Diwaleri	2.01	1.87	1.96	1.55	1.6	2.05	2.1	1.74	1.32
	Diwaleri to Chetanpuri	1.92	1.64	1.78	1.51	1.78	1.96	1.87	1.55	1
	Chetanpuri to Miragpur	1.37	1.83	1.83	1.83	2.19	1.83	1.42	1.14	1.64
	Sanpla (u/s) to Sanpla (d/s)	1.05	1.96	2.28	1.64	1.92	2.05	1.83	0.82	0.78
	Malira (u/s) to Malira (d/s)	1.14	1.51	1.6	1.69	2.33	2.51	1.37	1.14	1.28
	Khanjanpur (u/s) to Khanjanpur (d/s)	1.19	1.74	2.05	1.51	2.47	2.05	1.55	1.64	1.78
	Vihelna (u/s) to Vihelna (d/s)	1	1.28	1.6	1.42	1.92	1.46	1.6	1.23	1.23
	Mansurpur (u/s) to Mansurpur (d/s)	1	1.46	1.51	1.78	2.05	1.6	1.42	1.19	1.87
	Mansurpur (d/s) to Ancholi	1.32	1.6	1.55	1.69	2.01	1.64	1.51	1.46	2.33
	Ancholi to Pitlokar	1.51	1.6	1.51	1.51	1.83	1.51	1.51	1.6	2.51
Smoot(1988)	Rastam to Diwaleri	7.73	7.45	4.92	7.69	3.91	6.35	15.7	5.48	6.75
	Diwaleri to Chetanpuri	8.61	7.57	4.06	7.23	3.14	6.39	11.4	4.44	5.57
	Chetanpuri to Miragpur	6.06	6.15	3.78	6.81	3.51	5.33	7.32	3.33	8.8
	Sanpla (u/s) to Sanpla (d/s)	3.07	4.28	4.19	3.82	2.91	4.23	4.63	2.26	2.76
	Malira (u/s) to Malira (d/s)	2.39	2.99	2.93	2.98	2.97	3.92	3.14	2.33	2.9
	Khanjanpur (u/s) to Khanjanpur (d/s)	2.63	3.41	3.84	2.87	2.9	3.84	3.26	2.77	3.46
	Vihelna (u/s) to Vihelna (d/s)	2.51	2.9	3.36	2.85	2.6	3.25	3.52	2.3	2.84
	Mansurpur (u/s) to Mansurpur (d/s)	2.38	3.11	3.16	3.41	2.68	3.26	3.3	2.33	3.83
	Mansurpur (d/s) to Ancholi	2.55	3	2.92	3.06	2.37	2.97	3.21	2.34	4.23
	Ancholi to Pitlokar	2.84	2.82	2.8	2.67	2.27	2.84	3.26	2.26	4.03
Moog and Jirka(1998)	Rastam to Diwaleri	0.55	0.53	0.86	0.43	0.88	0.69	0.28	0.68	0.42
	Diwaleri to Chetanpuri	0.47	0.46	0.94	0.44	1.23	0.66	0.35	0.75	0.39
	Chetanpuri to Miragpur	0.48	0.63	1.04	0.57	1.35	0.73	0.41	0.74	0.4
	Sanpla (u/s) to Sanpla (d/s)	0.74	0.99	1.17	0.93	1.43	1.05	0.85	0.79	0.61
	Malira (u/s) to Malira (d/s)	1.04	1.09	1.18	1.23	1.7	1.38	0.94	1.06	0.96
	Khanjanpur (u/s) to Khanjanpur (d/s)	0.98	1.1	1.15	1.14	1.85	1.15	1.03	1.29	1.11
	Vihelna (u/s) to Vihelna (d/s)	0.87	0.96	1.03	1.07	1.6	0.97	0.98	1.17	0.94
	Mansurpur (u/s) to Mansurpur (d/s)	0.92	1.02	1.03	1.13	1.67	1.06	0.93	1.11	1.05
	Mansurpur (d/s) to Ancholi	1.13	1.15	1.15	1.2	1.85	1.2	1.02	1.36	1.18
	Ancholi to Pitlokar	1.15	1.23	1.17	1.22	1.75	1.15	1	1.54	1.34

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IHP	13.22	12.42	5.28	13.8	3.44	8.81	55.6	6.74	10.91
Rastam to Diwaleri									
Diwaleri to Chetanpuri	16.62	13.19	3.65	12.2	2.16	9.01	29.7	4.5	7.83
Chetanpuri to Miragpur	8.72	8.46	3.13	10.4	2.59	6.32	12.7	2.66	17.94
Sanpla (u/s) to Sanpla (d/s)	2.29	3.97	3.69	3.28	1.81	3.85	4.74	1.29	1.97
Malira (u/s) to Malira (d/s)	1.35	2.02	1.91	1.96	1.82	3.16	2.28	1.29	1.96
Khanjanpur (u/s) to Khanjanpur (d/s)	1.64	2.56	3.16	1.86	1.71	3.16	2.39	1.7	2.62
Vihelna (u/s) to Vihelna (d/s)	1.54	1.96	2.53	1.86	1.45	2.41	2.79	1.23	1.9
Mansurpur (u/s) to Mansurpur (d/s)	1.38	2.2	2.26	2.55	1.51	2.38	2.5	1.27	3.2
Mansurpur (d/s) to Ancholi	1.51	2.02	1.91	2.06	1.18	1.96	2.33	1.23	3.75
Ancholi to Pitlokar	1.82	1.78	1.77	1.61	1.1	1.82	2.4	1.13	3.34
Jha, Ojha and Bhatia (2000)									
Rastam to Diwaleri	5.9	5.69	5.01	5.43	4.34	5.55	7.64	5	4.93
Diwaleri to Chetanpuri	6.03	5.49	4.55	5.26	4.16	5.48	6.6	4.49	4.23
Chetanpuri to Miragpur	4.81	5.29	4.47	5.48	4.62	5.04	5.18	3.69	5.79
Sanpla (u/s) to Sanpla (d/s)	4.56	5.62	5.31	5.75	4.41	5.44	5.48	3.22	4.95
Malira (u/s) to Malira (d/s)	3.49	4.78	4.97	4.34	4.15	4.83	4.8	2.91	3.06
Khanjanpur (u/s) to Khanjanpur (d/s)	3.21	4.15	4.28	4.02	4.37	4.73	4.16	3.09	3.32
Vihelna (u/s) to Vihelna (d/s)	3.29	3.88	3.93	4.02	4.44	5.01	3.83	3.26	3.64
Mansurpur (u/s) to Mansurpur (d/s)	3.35	4.11	4.33	3.93	4.44	4.87	3.92	3.61	4.02
Mansurpur (d/s) to Ancholi	3.45	4.25	4.67	3.83	4.49	4.67	4.04	3.89	4.3
Ancholi to Pitlokar	3.31	3.96	4.4	3.77	4.23	4.35	4.1	3.66	3.96

Table 4: Performance Evaluation of PEs with DOBT

Correlation Coefficient										
Authors	Mar	April	May	July	Aug	Sep	Nov	Dec	Jan	Mean
O'Conner & Dobbins(1958)	0.8	0.46	0.29	0.19	0	0.7	0.7	0.2	0.2	0.4
Churchill et al.(1962)	0.8	0.46	0.33	0.19	0	0.7	0.7	0.2	0.2	0.41
Krenkel and Orlob(1962)	0.8	0.51	0.3	0.27	0	0.7	0.7	0.2	0.2	0.41
Owens(1964)	0.8	0.44	0.3	0.17	0	0.7	0.7	0.2	0.2	0.4
Langbein and Durum(1967)	0.8	0.49	0.34	0.23	0	0.7	0.7	0.2	0.2	0.42
Cadwallader and McDonnell(1	0.8	0.49	0.3	0.23	0	0.7	0.7	0.2	0.2	0.41
Thackston and Krenkel(1969)	0.7	0.69	0.65	0.56	0	0.8	0.9	0.1	0.4	0.54
Parkhurst and Pomeroy(1972)	0.8	0.48	0.28	0.23	0	0.7	0.7	0.2	0.2	0.4
Tsivoglou and Wallace(1972)	0.8	0.31	0.31	0.2	0	0.1	0.6	0.1	0.1	0.27
Smoot(1988)	0.8	0.51	0.32	0.27	0	0.7	0.7	0.2	0.2	0.42
Moog and Jirka(1998)	0.5	0.48	0.02	0.31	0	0.5	0.6	0.1	0.3	0.31
IHP	0.8	0.47	0.32	0.21	0	0.7	0.7	0.2	0.2	0.41
Jha, Ojha & Bhatia	0.8	0.82	0.8	0.77	0.7	0.7	0.9	0.5	0.7	0.74

Standard Error										
Authors	Mar	April	May	July	Aug	Sep	Nov	Dec	Jan	Mean
O'Conner & Dobbins(1958)	0.8	0.87	0.73	0.71	0.2	0.3	0.8	1	0.8	0.7
Churchill et al.(1962)	0.7	0.87	0.71	0.71	0.2	0.3	0.8	1	0.8	0.69
Krenkel and Orlob(1962)	0.8	0.82	0.72	0.67	0.2	0.4	0.8	1	0.8	0.69
Owens(1964)	0.8	0.88	0.72	0.72	0.2	0.3	0.8	1	0.8	0.7
Langbein and Durum(1967)	0.7	0.85	0.7	0.69	0.2	0.3	0.8	1	0.8	0.68
Cadwallader and McDonnell(1	0.8	0.84	0.72	0.69	0.2	0.3	0.8	1	0.8	0.69
Thackston and Krenkel(1969)	1.1	0.66	0.51	0.52	0.2	0.3	0.6	1.1	0.7	0.61
Parkhurst and Pomeroy(1972)	0.8	0.85	0.73	0.69	0.2	0.3	0.8	1	0.8	0.7
Tsivoglou and Wallace(1972)	0.8	0.98	0.72	0.7	0.2	0.6	1	1.1	0.9	0.78
Smoot(1988)	0.8	0.82	0.71	0.67	0.2	0.4	0.8	1	0.8	0.68
Moog and Jirka(1998)	1.3	0.85	0.85	0.65	0.2	0.5	0.9	1.1	0.8	0.79
IHP	0.7	0.86	0.71	0.7	0.2	0.3	0.8	1	0.8	0.69
Jha, Ojha & Bhatia	0.8	0.5	0.39	0.38	0.1	0.3	0.4	0.8	0.5	0.47

Normal Mean Error										
Authors	Mar	April	May	July	Aug	Sep	Nov	Dec	Jan	Mean
O'Conner & Dobbins(1958)	2.1	1.72	0.55	2.08	0.2	1	4.3	1	3.2	1.78
Churchill et al.(1962)	2	1.76	0.47	2.12	0.1	1	5.3	0.7	3.1	1.83
Krenkel and Orlob(1962)	1.2	0.87	0.5	0.93	0.5	0.5	1.2	1	1.6	0.91
Owens(1964)	4.7	4.03	1.39	4.95	0.6	2.4	12	1.9	7.2	4.33
Langbein and Durum(1967)	0.9	0.76	0.12	0.9	-0.1	0.4	2.1	0.2	1.5	0.75
Cadwallader and McDonnell(1	0.4	0.22	-0.1	0.3	-0.2	-0	0.7	0.1	0.7	0.23
Thackston and Krenkel(1969)	-0.1	-0.3	-0.4	-0.2	-0.4	-0.4	-0.1	-0.1	0	-0.2
Parkhurst and Pomeroy(1972)	-0.5	-0.5	-0.7	-0.5	-0.7	-0.6	-0.3	-0.6	-0.3	-0.5
Tsivoglou and Wallace(1972)	-0.6	-0.6	-0.6	-0.6	-0.5	-0.7	-0.6	-0.6	-0.5	-0.6
Smoot(1988)	0.1	-0.1	-0.3	-0	-0.3	-0.2	0.2	-0.1	0.3	-0.1
Moog and Jirka(1998)	-0.7	-0.8	-0.8	-0.8	-0.6	-0.8	-0.8	-0.7	-0.7	-0.8
IHP	0.1	0	-0.4	0.11	-0.6	-0.2	1	-0.3	0.5	0.01
Jha, Ojha & Bhatia	0.2	0.05	-0.1	0.03	0.1	-0.1	0.1	0.2	0.2	0.06

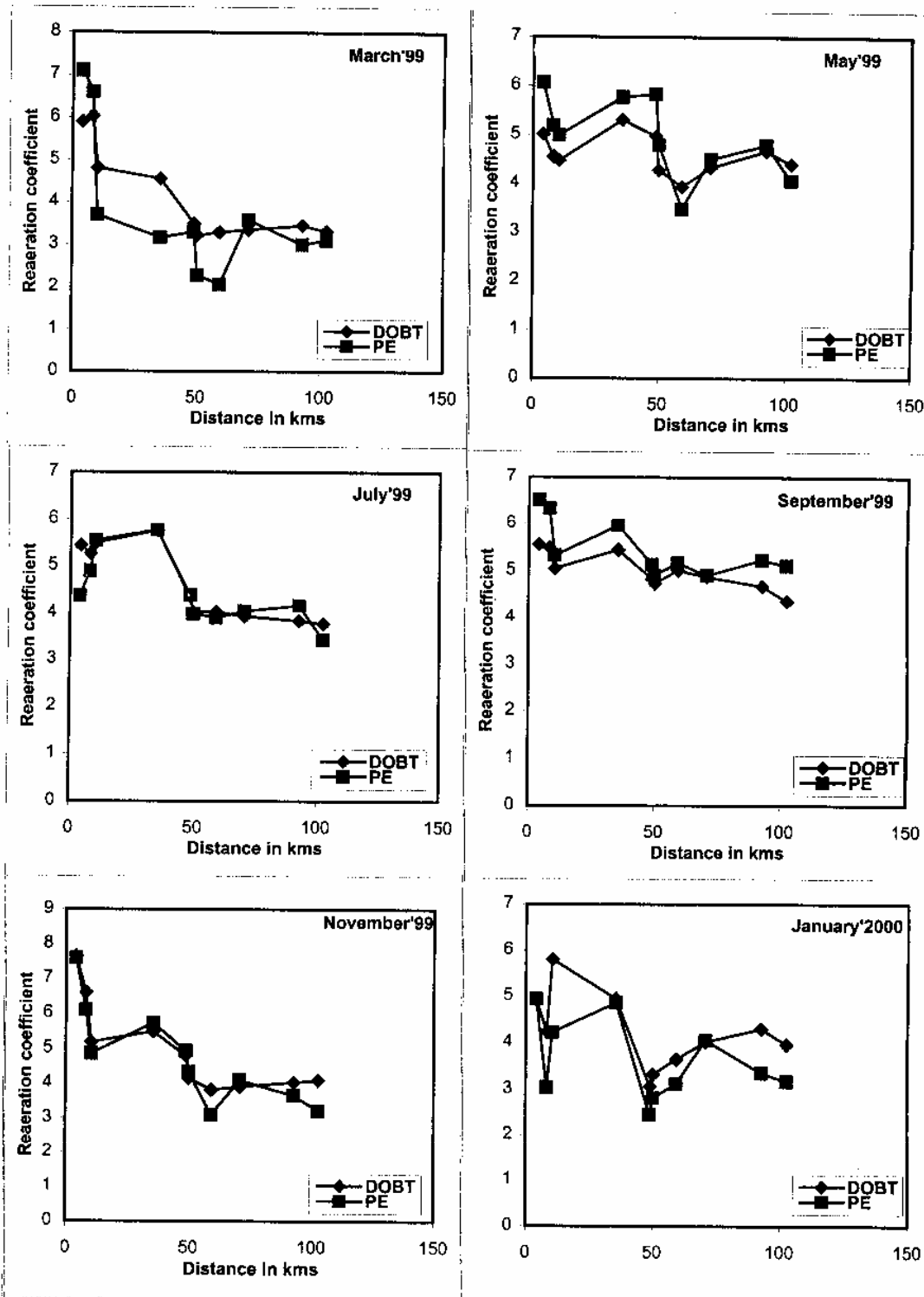| Mean Multiplicative Error										
Authors	Mar	April	May	July	Aug	Sep	Nov	Dec	Jan	Mean
O'Conner & Dobbins(1958)	2.5	2.22	1.53	2.23	1.3	1.7	3.3	1.8	3.3	2.21
Churchill et al.(1962)	2.2	2.12	1.49	2.07	1.4	1.8	3.2	1.7	3	2.11
Krenkel and Orlob(1962)	2.1	1.82	1.48	1.84	1.4	1.5	2.1	1.9	2.4	1.85
Owens(1964)	3.9	3.61	2.26	3.59	1.5	2.8	5.8	2.4	5.4	3.48
Langbein and Durum(1967)	1.7	1.62	1.3	1.62	1.3	1.5	2.1	1.5	2.2	1.66
Cadwallader and McDonnell(1	1.4	1.34	1.21	1.45	1.4	1.3	1.6	1.4	1.7	1.42
Thackston and Krenkel(1969)	1.2	1.34	1.69	1.39	1.7	1.7	1.3	1.3	1.2	1.43
Parkhurst and Pomeroy(1972)	1.9	2.26	3.02	2.3	3.6	2.8	2.1	2.4	1.8	2.46
Tsivoglou and Wallace(1972)	2.7	2.75	2.79	2.73	2.1	3	2.9	2.4	2.4	2.62
Smoot(1988)	1.3	1.28	1.38	1.4	1.4	1.3	1.4	1.3	1.4	1.35
Moog and Jirka(1998)	4.4	5.16	4.58	5.04	2.8	5.6	6.5	3.2	4.6	4.64
IHP	1.9	1.87	1.77	2.11	2.3	1.8	2.1	1.9	1.7	1.93
Jha, Ojha & Bhatia	1.2	1.12	1.11	1.06	1.1	1.1	1.1	1.2	1.2	1.13

FIG.5: COMPARISON OF REAERATION COEFFICENTS
ESTIMATED BY TWO METHODS

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reaeration coefficient (K2) obtained using DOBT. The result shows better "goodness of fit" and lower "differential or multiplicative errors". Fig.6 illustrates the performance evaluation of all the most commonly used PEs including equation developed in the present study (Jha, Ojha and Bhatia). It can be seen that the present equation shows highest correlation coefficient (0.75) and minimum mean multiplicative error (MME) (1.15). The mean multiplicative error is found to be best among other error estimation techniques.

The values of reaeration coefficient (K2) in Kali River vary between 5-8 in upper reaches and 2-5 in lower reaches. The temperature has a significant role in estimation of reaeration coefficient and the PE developed in the present study is for the temperature of 20°C. The reaeration coefficients can be changed into water temperature using the equation 8 and the saturated dissolved oxygen at different stream water temperature has been evaluated using following equation:

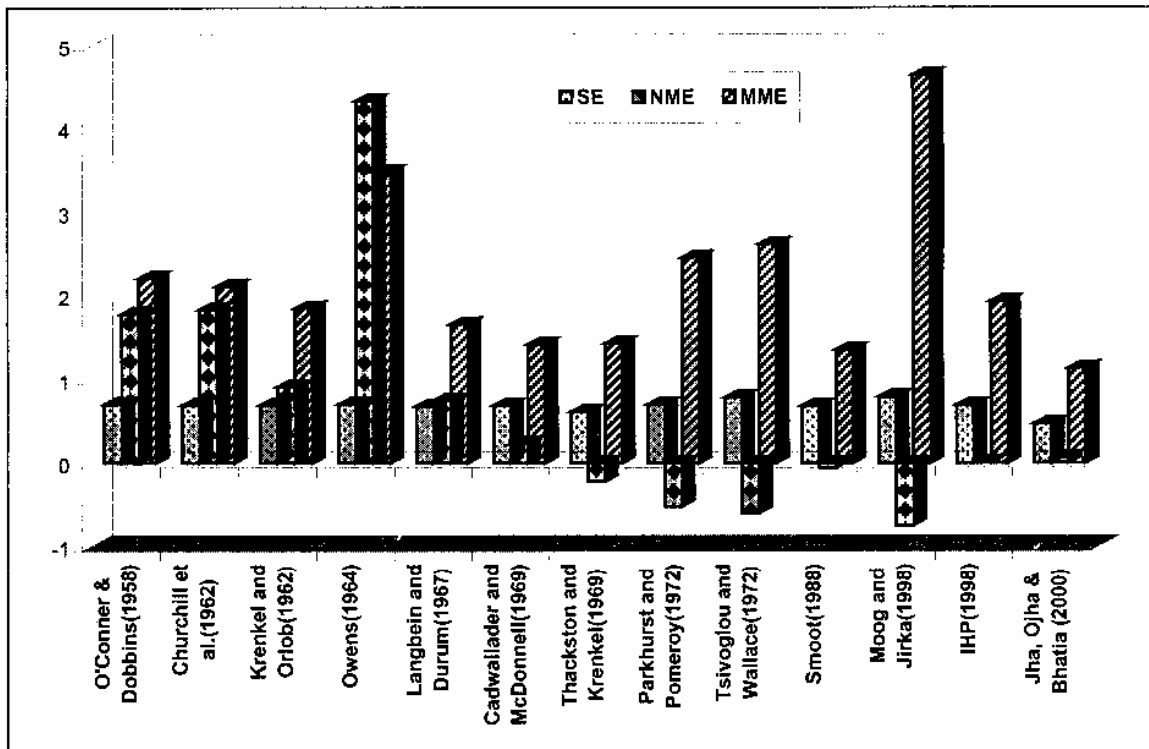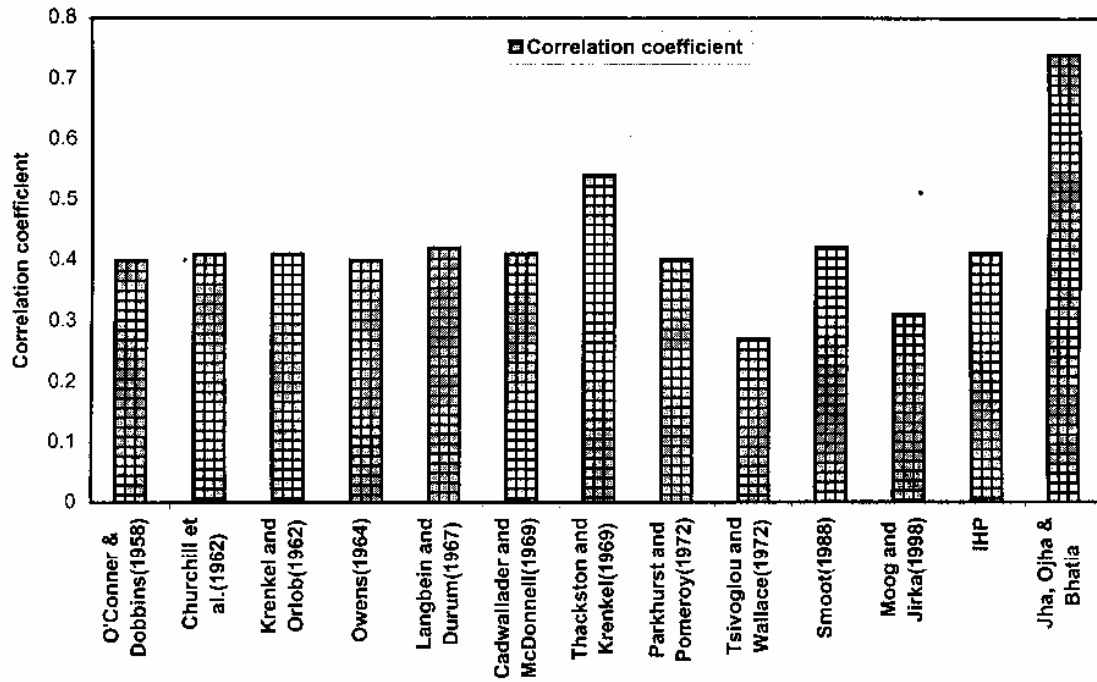$$DO_{sat} = 14.61996 - 0.4042T + 0.00842T^2 - 0.00009T^3 \qquad \ldots 16$$

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FIG.6: PERFORMANCE EVALUATION OF REAERATION COEFFICIENT

5.0 CONCLUSIONS

The following conclusions have been drawn from the results:

1. The predictive reaeration equations developed in the present study showed promising results and can be used to determine reaeration in river Kali without using DOBT technique which is exhaustive, costly and time consuming. For known velocity, depth and temperature reaeration coefficient can be obtained easily and can be used as input to water quality modelling.

2. The developed predictive equation can be sucessfully used for rivers having similar & homogeneous hydraulic and geographic conditions.

3. Better results can be obtained if radioactive tracer technique is also used with the DOBT and PE approaches. However, in the tracer technique high precautions are required to avoid the effect of radioactive tracers on aquatic and human life.

4. Longitudinal profile of the organic matter illustrates that at Mansurpur the water quality of the river Kali has been deteriorating exceedingly due to disposal of untreated municipal, industrial and sugar mill effluents of Muzaffarnagar town. As can be seen from Fig.4, each DO and BOD has significant decrease and increase respectively at Mansurpur as compared to Malira Bridge.

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