Water Quality Predictions in the Mixing Zone of River Kabini at Nanjangud area, Karnataka, India

Jyothi M R[1*] and Raghavendra H U[1]

[1]Department of Civil Engineering, M S Ramaiah Institute of Technology, Bangalore, India

*Corresponding author. Email: jyothimr@msrit.edu

Abstract

The scenario of unauthorized encroachments and anthropogenic activities in the riverbed area brings our attention towards fast deterioration of water quality in rivers and subsequent damage to the ecosystems thereof. More precisely, number of drains discharging wastewater into rivers and solid waste dumping sites along the river banks pose threat to the aquatic community, recreational areas, quality of surface and ground water, and also results into problems, such as sedimentation and erosion. In view of the need for conservation of natural resources, developmental plans in the riverbed area are being proposed, due to this type of pollution, Dissolved oxygen (DO) concentrations in streams and rivers are below specified limits and adversely affect aquatic biota. The continuous discharge of wastewater effluents into the natural rivers demands careful control of the amount and quality of pollutants present in such effluents. In many situations, the discharge of industrial and municipal effluents into the rivers will results in the information of mixing zone. It consist of two zones: (a) Limited use zone (LUZ) and (b) Zone of Passage (ZOP), The present study deals with the water quality predictions in the mixing zone, with a drain from the city entering the river from the pipe through a bank outfall. The field data were collected during lean flow at selected points in river Kabini. The city's wastewater is being used to investigate the river's dispersion properties. In this survey, the data were obtained on the cross sectional distribution of dissolved solids (measured by specific conductance). The peak values of conductance occurred near the discharge shoreline during the study. Based on the results of conductivity observations, the width and lateral dispersion coefficients of the outflow plumes of various transects are determined. It was found that the width of the effluent plume flowing into Transect depends on the depth of the channel. The lateral variance coefficient is a function of the depth of the channel, not the breadth of the river under inquiry, according to the data analysis. The field data were also utilized to estimate decay rates of CBOD and NBOD as well as reaeration rate for each reach in the study segment of river.

The calibration of the model for lateral mixing is carried out using conductivity distribution data, which is followed by the calibration of DO model. Then the calibrated DO model was utilized for the prediction of DO in the river due to several viable technological options. The results indicate that, for given values of effluent CBOD and NBOD, the in stream DO would increase with increase in lateral limit use zone boundary.

Keywords: Dissolved Oxygen, Limited use zone, Zone of passage, Reaeration, Urbanization

Introduction

Rivers serve multifarious water use needs such as irrigation, power generation, navigation, recreation, waste disposal, fish and wild life habitat, etc. there has been a degradation of water quality in rivers due to discharge of waste water from agriculture, urbanization, industrialization, mining, storm water carrying flushed materials in its run-off, and other human activities. Nuisance aquatic plants and algal growth also takes place due to nutrient enrichment. As a result of decomposition of organic material and growth of nuisance plant and algae, dissolved oxygen (DO) depletion has been observed. DO are important water quality that affect the health of the river and therefore more important to keep DO at appropriate levels (Doneker, R. L et al.,1991). Wastewater effluents discharged into streams and rivers can some time have different time history of the discharge of the pollutants, which can vary from instantaneous to continuous (Stephen P. Schreiner et al., 1999). In some cases a finite time discharge of the pollutant occurs (viz., batch discharge from industries, storm water runoff, accidental spills, etc) in which case, we need an assessment of exposure time of DO violation (Jirka, G. H et al.,1996). The effects of such discharges on the river water quality are transient in nature, which are assessed by the duration of passage of concentration cloud and the concentration levels at a given downstream station. Here it is important to know the time of exposure of the transient cloud to aquatic biota and population dependent on dissolved oxygen with particular emphasis on the hours of violation of a specified DO standard.

In order to maintain desirable levels of river water quality, the probable impact of pollutant loads on river ecosystem is analysed. Several methods are adopted in such analyses including field and laboratory experimentation, simulation and interpretation. In the management of river water quality, mathematical models are an efficient tool for evaluating the efficacy of various management methods (Rankovic. V et al., 2010).

There are two primary reasons for using mathematical modelling to create representations of natural water systems (Halappa Gowda. T. P et al., 1984). The first is the need to improve one's understanding of the cause-and-effect relationships at work in water quality, and the second is to put that knowledge to use in the decision-making process. Water quality models are essentially synthesises of a variety of water transport phenomena, intricate reaction kinetics, and residual inputs provided externally. The water quality model builder is one aspect of a three-part interaction that also includes a specialist who develops process details and a manager who is concerned with the problem specification and, in some ways, its resolution. One such class of models deals with the dissolved oxygen (DO) regime in rivers. There are two types of river pollutants which are discussed below:

1. Point sources:

- Municipal wastewater: This includes sewage from homes and businesses. Sewage and fertilizers contain many compounds, including microorganisms, as well as nutrients such as nitrates and phosphates.
- Industrial effluents: The impact of industrial effluents is determined not only by their general characteristics, such as BOD and the amount of SS, but also by their inorganic and organic content, which can vary greatly within and between companies.

2. Non-point sources:

  - A non-point source delivers pollutants indirectly. The water that eventually reaches our homes is frequently polluted and contaminated with disease-causing microbes. Agricultural runoff, or water from fields that flows into rivers, is another major source of water pollution because it contains fertilisers and pesticides.

Organic matter pollution enters waterways in numerous forms, including leaves and chopped grass, as well as streams of food and feed for livestock. Pollution also occurs when other suspended solids, such as sludge and soil, leach from fields, construction and logging areas, urban areas and river banks that are eroded during rain.

Materials and Methods

Mixing Zone Concept

A mixed zone is defined as a water source that does not meet a specific water quality target in an adjacent water source, such as a water source that meets the water source and water source standards (water quality standards handbook, 2014; US New England, Inc. 2002).

In ultimate disposal of wastewater in rivers, mixing zones are created, when effluents are discharged through bank or diffuser outfalls that may result in plumes which tend to hug the shore line for considerable distance below the outfall. The effluent spreading is gradual, resulting in concentration gradient being set up in the lateral direction for considerable distances (50 to 100 times channel width). In contrast, the vertical direction exhibits uniform concentration in a shorter distance below the outfall (viz., 50 to 100 times channel depth). Finally, the transverse concentration distribution achieves uniformity well below the runoff (John Veil A, 1994).

The "mixing zone length" is the distance between the output and the cross section where the concentration becomes uniform. During outflow, the drainage stretches across the entire width of the river, which is termed as the "crossing distance". The concentration of the pollutant of concern may exceed the permitted threshold in a segment of the river's cross-section within the mixing zone, which is referred to as the "Limited Use Zone" (LUZ). The 'Zone of Passage' is the remaining section that provides acceptable habitat for the biota (ZOP) (Beltaos. S, 1979). The prominent features of a mixing zone are given in Figure 1.

In the present study, this concept of mixing zone has been adopted to predict the plume dispersion and its concentration profiles in lateral directions (i.e., across the river).

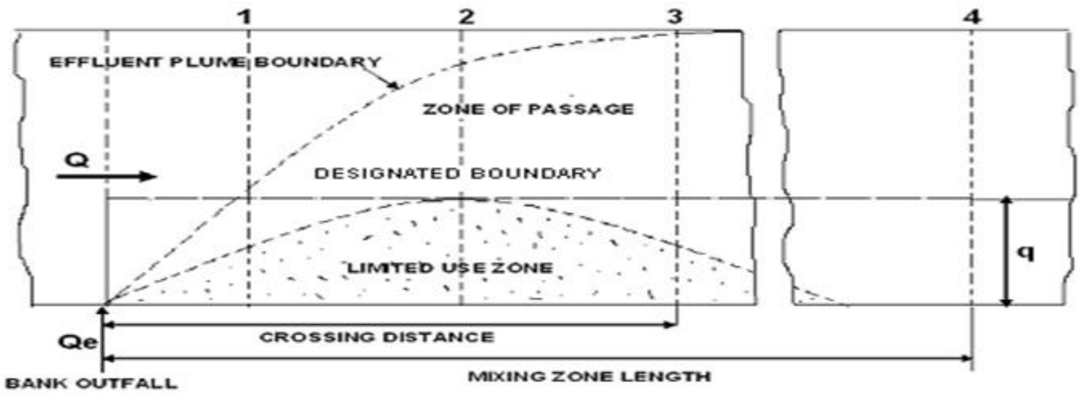


Figure 1: Schematic Diagram of Mixing Zone

In a mixing zone, the concentration profiles of a pollutant vary at different cross sectional widths. This is due to the hydraulic and transport characteristics of the river course. The typical variation of a pollutant concentration at one third lateral width from the bank of the outfall at different cross sectional widths has been presented in Figure 2. It can be seen from the figure that by the end of mixing zone length, the lateral concentration profile will be uniform across the entire width of the river.

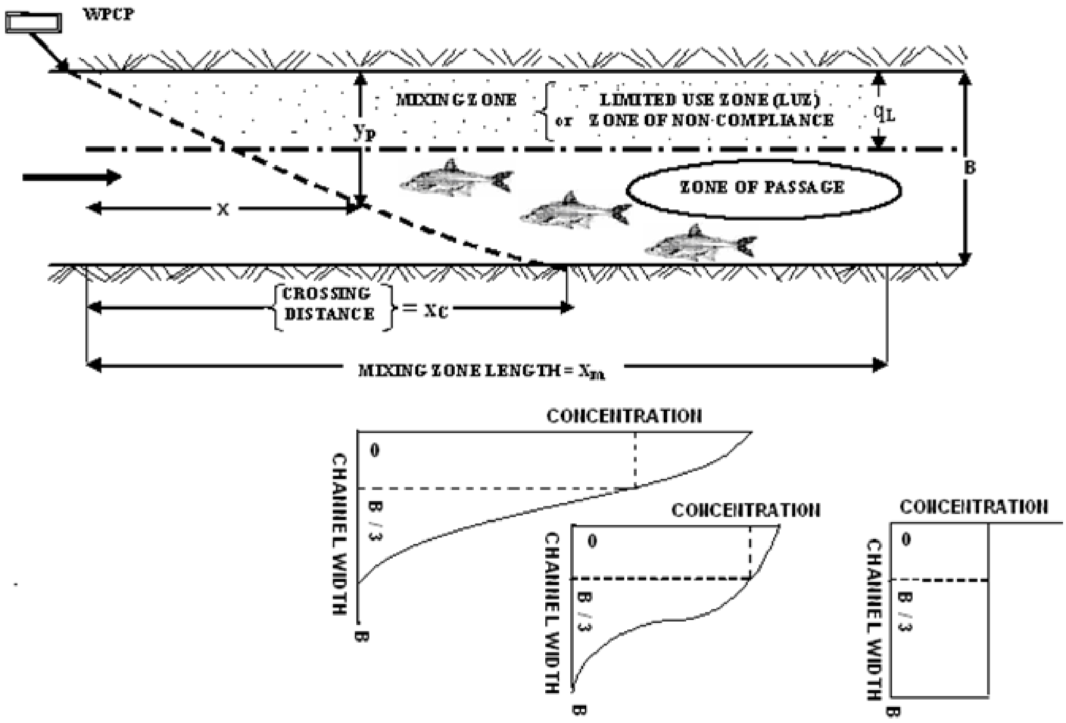


Figure 2: Lateral Concentration Profiles in Mixing Zone

Importance of Dissolved Oxygen in River Water

DO is considered to be the key parameter which indicates the health of river (Skowysz A, 2011). The oxygen resources of a running stream are the most prevalent criterion used by regulatory agencies (Mirosław Skorbiłowicz, et al.,2017). Low DO levels or anaerobic conditions cause an unbalanced ecology, fish death, and smell and other aesthetic issues. The discharge of municipal and industrial wastes as well as urban and other nonpoint source pollutants necessitates a continuing effort in understanding the DO resources of surface water.

Factors and processes affecting Dissolved Oxygen in Streams

The DO levels in streams and rivers are affected by several sources and sinks. The important sources are:

- Reaeration from atmosphere.
- Photosynthetic oxygen production.
- The DO input from tributaries and effluent loadings.

The major sinks of DO are:

- Oxidation of carbonaceous and nitrogenous waste materials given by carbonaceous biochemical oxygen demand (CBOD) and nitrogenous oxygen demand (NOD)
- Sediment oxygen demand (SOD)
- Oxygen utilization by aquatic plants for respiration

The general mass balance equation for DO concentrations, C in a segment volume, V can be written as

V dc/dt = Reaeration + (photosynthesis - respiration) + DO input - CBOD & NOD oxidation - SOD ± DO transport into or out of segment.

Stream Tube Concept

(a) For Strength studies

In this approach, the river's cross-section is divided into many vertical strips called "flow tubes" with the same flow in each flow tube. Yotsukura and Cobb (Yotsukura, N, et al., 1972) created the basic notion of this model, which treats the partial cumulative discharge (q) as an independent variable rather than the lateral distance (y). The lateral concentration distribution (c (x, q) suggested by the flow tube model is a function of q since the vertical strips transport equal emissions. The classic graph C (x, y) Vs y, which knows the relationship between q and y in distinct transects, can be translated into these distributions.

The equations for the flow pipe model are based on a number of assumptions, including that the concentration distribution in remote areas is unaffected by the near-field mixing process, and that river channel flows are distributed uniformly and vertically. In shallow rivers, the distance required to achieve vertical uniformity is very short (50-100 times the depth of the canal). In addition, it is assumed that the density of the wastewater is the same as the density of the incoming water and does not take into account the transfer due to vertical dispersion.

The predictions for various scenarios in this study are based on the above concept and assumptions.The reason for assuming stream tube concept is explained in Figure 3. In the figure it is observed that there is a significant variation of flow with respect to width at various cross sections of river course. It would be difficult to simulate such flow conditions in the conventional mathematical models that have been used in such studies. Hence, the stream tube concept has been adopted to account for such conditions.

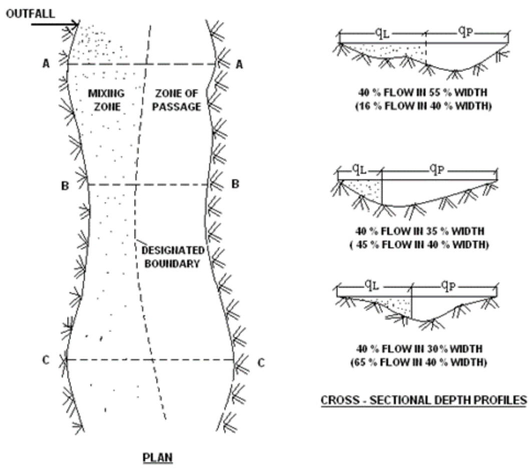


Figure 3: Depth – Flow Relationship in Mixing Zone

Field Survey Procedure

The field survey's purpose is to collect data in six sections on velocity and background water properties, as well as the distribution of the main lateral factors of interest. The specifics of field investigations are usually determined by the site's unique circumstances. A general field investigation procedure is outlined below to help you understand and appreciate it.

The transect location can be based on a conservative parameter (in this case, the conductivity as conservative parameter) preliminary in-situ measurements at selected locations of access, to establish the approximate longitudinal limit of the mixing zone. Selected transect points on the map should be marked so that during subsequent study they can be easily located in the field. At least 15 points at known lateral distances measured by a reference shoulder, the cross-sectionality should be measured (usually a drainage shoulder). Velocity measurements should also be made on two cross-sections, but ideally on all cross-sections, in accordance with the measuring process guidelines. Samples of water near the edge of the water entry and outlet and at every position in the cross section where the depth and flow velocity are measured. To explain the possible influence of fluctuations in the quality and flow of wastewater on the concentration in the stream, sampling is performed either along the same snail, starting from the mouth and moving to successive sections downstream, or during 24 hours. intensive research, sampling at each point with an interval of 3-4 hours (Eheart W J, 1990).

In-situ measurement include temperature, pH, conductivity, and dissolved oxygen by collecting samples. The samples for non-conservative contaminants were analysed in the laboratory. In some circumstances the dye solution may be required to collect data on the properties of the lateral distribution of the river continually (Skowysz A, 2011). This is particularly useful for simulating wastewater discharges from a proposed repository and for considering the transfer of existing discharges.

Data Analysis Procedure

This forms the continuation step after the field survey. For determining parameters for modelling, data acquired during a field examination is employed (Cox B A, 2003). The following computations are executed using the field survey data as input via a programme called MIXANDAT.

- ☞ Average speed and depth of each transect,
- ☞ Remedy of the transverse speed distributions when velocities are not measured,
- ☞ The transect speed factor for every transect.
- ☞ A modification of the cross-sectional distributions of conservatory materials
- ☞ Average speed and depth of each transect (required to evaluate the dispersion characteristics).

For mixing zone water quality predictions, there is a necessity of intensive field measurements and data collection. This is because of significant variation in hydraulic characteristics of a riverine system. Figure 4 explains clearly the physical and water quality parameters measurements in the study stretch of a riverine system. Figure 4 also shows the variations of measured concentration profiles of a tracer element at different transects. These measurements would be utilized to compare with the predicted concentrations.

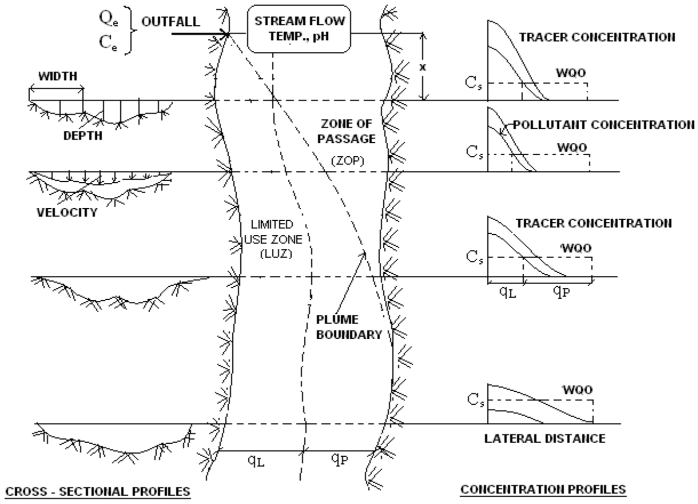


Figure 4: Field Data Requirements

For mass flow and dispersion calculations, the net concentration value of the substance is derived by subtracting the measured value from the background value of the substance in the river. If the net concentration is negative, it is set to 0.

Effects of Background Concentration and Hydraulic Characteristics of River Water

When the background concentrations are not negligible in a river just upstream of outfall, it is possible to include their effect in predicting the concentrations downstream of outfall. The distribution of the background concentration at the river crossing is generally uniform and the degradation rate for background pollutants may be low compared to the sewer discharge (Halappa Gowda T P, 1980). When numerous points are drawn into the riverbed it will rely on the distance between discharges, the river flow, and the other hydraulic features of this channel. The upstream flows close above the following downstream flow will have several points.

It is insufficient to just predict the affects at low flow conditions when determining whether the outfalls may be treated individually; all stream flow conditions should be considered.

When there is a lot of water in the stream, it might cause a lot of overlapping of the discharges. (Eheart W J, 1990) shown that it is worst if neighbouring areas do not overlap appreciably at any stream flow, i.e. at low stream flow, and thus independent regulation design is required. Further, the decay and Reaeration coefficient could decreases with the increased flow. According to Bhargava (Bhargava D S, 1986), BOD assimilation in India's Ganga and Yamuna rivers is extraordinarily quick. The BOD rate constant ranged from 1.5 to 5.5 per day. As a result, the impact of one outfall on another is determined by the kinetic parameters and stream flow, as well as the magnitude of the discharges and the distances between them.

Deoxygenation in River

The rate Deoxygenation, Kd can be determined from the equation

L = L0 e –kdt ... (1)

i.e. $K_d = \frac{1}{\Delta t}\log\frac{L_0}{L_t}$ ... (2)

Δt = Time of travel between two points under consideration, in days

L0 = Ultimate upstream BOD in mg/l at travel time t = 0

Lt = Ultimate downstream BOD in mg/l at travel time ‘t’

T = Time of stream flow between upstream and downstream sampling points, in days.

Reoxygenation in River

There are several equations useful in determining Reoxygenation constants. The most commonly used equation is stated here in:

i. O’Connor and Dobbins (1958) formula

$K_a = \frac{(D_m\, u)^{0.5}}{H^{1.5}}$ ... (3)

Where

DM = Molecular diffusion coefficient of oxygen in water (m2/sec)

U = Stream velocity, m2/sec

H = Mean stream depth, m

The molecular diffusion coefficient, DM is temperature dependent and is

Calculated from

DM = 2.4167 X 10-2 m3/sec at 20°C ... (4)

ii. Chruchill, Elmore and Buckingham Equation

$K_a = \frac{0.058\, U^{0.969}}{H^{1.673}}$ ... (5)

iii. Owen Edwards and Gibbs Equation

$K_a = \frac{0.245\, U^{0.670}}{H^{1.25}}$ ... (6)

Equation 3, 5, 6 are widely used for estimating Ka. A graphical representation of the data utilized in developing these three equations shown that each equation is applicable to streams of certain hydraulic characteristics (Covar A, 1976).

Modelling dissolved oxygen in rivers

It is clear from previous work that any (mechanical) model intended to simulate DO concentration in river should at least simulate the process described in the Fig.11 below. These processes occur in all modelled rivers, and most models use discretization, in which the river is divided into a series of ranges. Although mass storage must be done in the bank, the transit and conversion processes may cause changes in DO emphasis. A hydraulic model that replicates the transport of solute down the river and incorporates the biological, chemical, and physical transformation processes to be simulated is required to describe these processes in a mathematical model.

A vast amount of data will always be required for such a model (modelling of the processes in Figure 5), especially if it is to mimic time-dependent (i.e. dynamic) changes in the system. The first set of information required details the system's physical attributes, such as the network's design, the river system's division into sections, and the widths, depths, and lengths of these sections. The kind and magnitude of any flow structures, such as wier, whose impacts are to be replicated, will also be included in the site descriptions. The upstream boundary conditions, DO, BOD, ammonium, nitrate, and chlorophyll (or another indication of plant density), as well as pH and temperature, will be required in addition to the model system. The rate at which certain reactions take place is determined by temperature. These criteria must be a time series of each determinant over the period of interest for dynamic models. Boundary conditions must also be specified at the bottom of the system for more sophisticated hydraulic models. A similar collection of data for all impacts, such as tributaries or discharges flowing into the river at this time, as well as flow rates at all withdrawals, is necessary for each area.

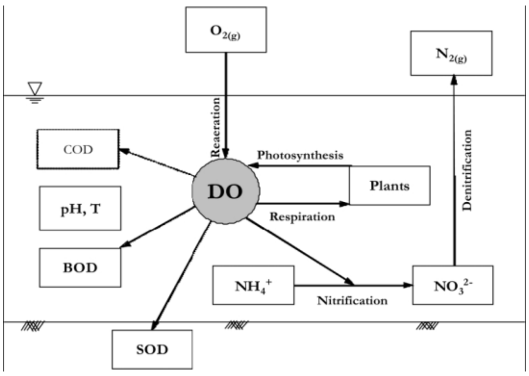


Fig 5: A representation of the major processes influencing the concentration of DO in rivers.
(Source: B. A. Cox, 2003)

Steady state Equation for Two Dimensional Mixing with First Order Decay

The distribution of non-conservative substances downstream of the mixing zone in a shallow river at equilibrium can be described by Gowda's [12] simplified 2D conservative diffusion equation, which can be written as

$$\frac{\partial L_c}{\partial x} = Eq \; \frac{\partial^2 L_c}{\partial q^2} - \frac{m_x K_d L_c}{u} \quad \text{... (7)}$$

Where

X = longitudinal distance below each source

Lc = concentration of pollutant of each source

U = depth of flow in the x-direction

Kd = 1st order decay rate co-efficient (assumed to be independent of X and Y)

Eq = diffusion factor, assumed to be constant at a given cross section

Q = a reference bank's partial cumulative discharge

mx = metric co-efficient

Multiplying the right hand side of the analytical expression by factor R' yields the concentration of a non-conservative material at a given point in the far field region. The following is the relationship:

R’ = exp (-Kd x/u) ... (8)

On the premise that the expression (mx Kd/u) is approximated by (Kd/u), u = average flow in the river stretch. This estimate is thought to be adequate in most practical scenarios.

The solution for a non-conservative pollutant discharge from a pipe outfall (i.e. point source) located at X = 0 and q=qe is given as

$$L_c = R'^{\left[\frac{L_a}{2\sqrt{\pi\emptyset}}\right]}\left[Z[\emptyset, P]\right] \quad \text{... (9)}$$

Subject to conditions, Le ->00, Qe -> 0

Where La = (Le Qe/ Q) and Z (Φ, P) is given by

$$Z(\Phi, P) = \left\{\sum_{n=0}^{00}\left[\exp\left\{-\frac{(2n+P_s-P)^2}{4\emptyset}\right\}\right] + exp.\{-(2n+P_s+P)^2/4\emptyset\} + \{\sum_{n=1}^{00}\{exp[-(2n+P_s - P)^2/4\emptyset]\}\} + exp\{-(2n+P_s+P)^2/4\emptyset\}\right\} \quad \text{... (10)}$$

Where

Φ = Dy x/Q2

Lc = in stream concentration of CBOD in mg/l

P = q/Q

Ps = qs/Q

Le = concentration of the pollutant in the effluent

Qe = Effluent flow rate

N = Number of images required to account for the effect on concentration of the reflection of the material from the channel banks.

If the pollutant contains oxidizable ammonia (measured by TKN) in the effluent, then resulting solution for the distribution of nitrogenous oxygen demand (NOD) is given by

$$L_n(x, P) = R' \left\{ \frac{N_a}{2\sqrt{\epsilon \pi \Phi}} \right\} Z(\emptyset, P) \quad \dots (11)$$

Here

Na = NeQe/q

Ne = concentration of NBOD in mg/l = 4.57 (TKN)

TKN = Total Kjeldahl Nitrogen Concentration, in mg/l (as N)

Qe = Effluent discharge in cumecs

Q = Total discharge in cumecs

R’ = exp (-Kn x/u)

Where Kn represent the decay rate due to the oxidation of NBOD.

Eqn. 11 gives the two dimensional NBOD distribution for pipe outfall located at a bank with the conditions x= 0, q= qs. As per stoichiometric relationships of nitrification, oxidation of one mg/l of TKN (to NO3) requires 4.57 mg/l of DO; and hence, NBOD = 4.57 (TKN). The range of values of Kn is approximately same as the Deoxygenation co-efficient Kd of CBOD. For deeper bodies of water, the value of Kn will range from 0.1 to 0.5 per day at 20°C; values greater than one per day are not uncommon.

The chemical equilibrium of solutions affects the concentration of some pollutants (non-ionized ammonia). Pollutant concentrations are computed by multiplying the Eqn. 9 forecast by a factor R” derived from chemical equilibrium considerations in such cases. In the instance of ammonia, for example, Eqn. 9's forecast would reflect total ammonia (i.e. sum of ionised and non-ionized forms of ammonia). The concentration of non-ionized ammonia is influenced by pH, temperature, and total ammonia concentration (Ct). Cu = R”X Ct is the formula describing the relationship between Cu and Ct, where R” is Gowda's factor (1980).

$$R^{"} = \frac{1.0}{\left[1+10^{(p\,Ka-pH)}\right]} \quad \dots (12)$$

Where pKa = [0.09018+ {2729.92/(T + 273.2)}]

in which Ka is dissociation constant for ammonia and pKa = -Log Ka.

This development is based on the premise that temperature and pH distributions in streams are uniform at various cross sections. For the vast majority of practical circumstances, this assumption is adequate.

Effect of Change in Stream Flow

A change in stream flow rate causes variations in depth h, velocity v, and the top breadth of river water surfaces. b. The following Leopold – Maddock equations, as stated by Gowda, are used to express changes in hydraulic parameters and type of travel (1980).

b1 = b2 (Q1/Q2)bex … (13)

h1 = h2 (Q1/Q2)hex … (14)

u1 = u2 (Q1/Q2)uex … (15)

In which bm, hm and um represents in order of the mean values of width, depth and velocity at flow Qm; and bi, hi and ui are exponents such that their sum is equal to unity, (here m = 1, 2).

The following expression for the reaerration rate co-efficient is obtained by Gowda (1983)

KaT2 = KaT1 θT2-T1 (Q1/ Q2)1.5 h'- 0.5u' … (16)

Here KaT1 represents the value of Reaeration rate co-efficient at a stream flow of Qi and a temperature of Ti (I = 1, 2).

Results and Discussion

River Hydraulic Measurements and Water Quality Monitoring

The study stretch of River Kabini has been divided into 6 transects starting from Transect 0 to Transect 6 (these transects are located in the longitudinal distance of 5.200 Km). However, the data collect at Transects 1 to 6 are used in the analysis, since transect 0 is a background of the effluent outfall. At each transect the measurements of various physical parameters, water quality parameters, of the riverine stretch and other required data were measured and tabulated. Figure 6 shows the variation of depth profile across the width of the river at each transects.

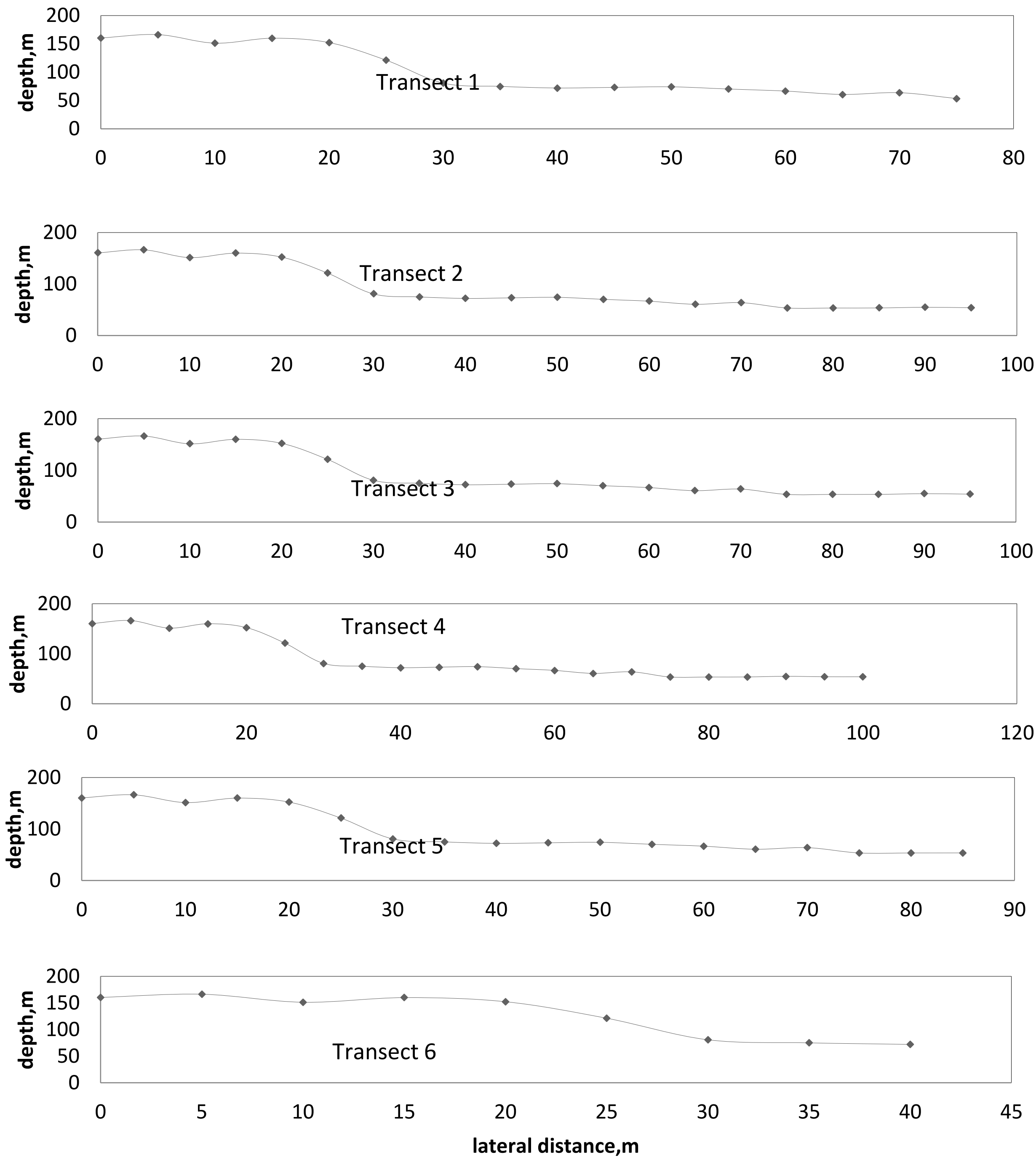


Figure 6: Depth Profiles at Various Transects in the Study Stretch of River Kabini

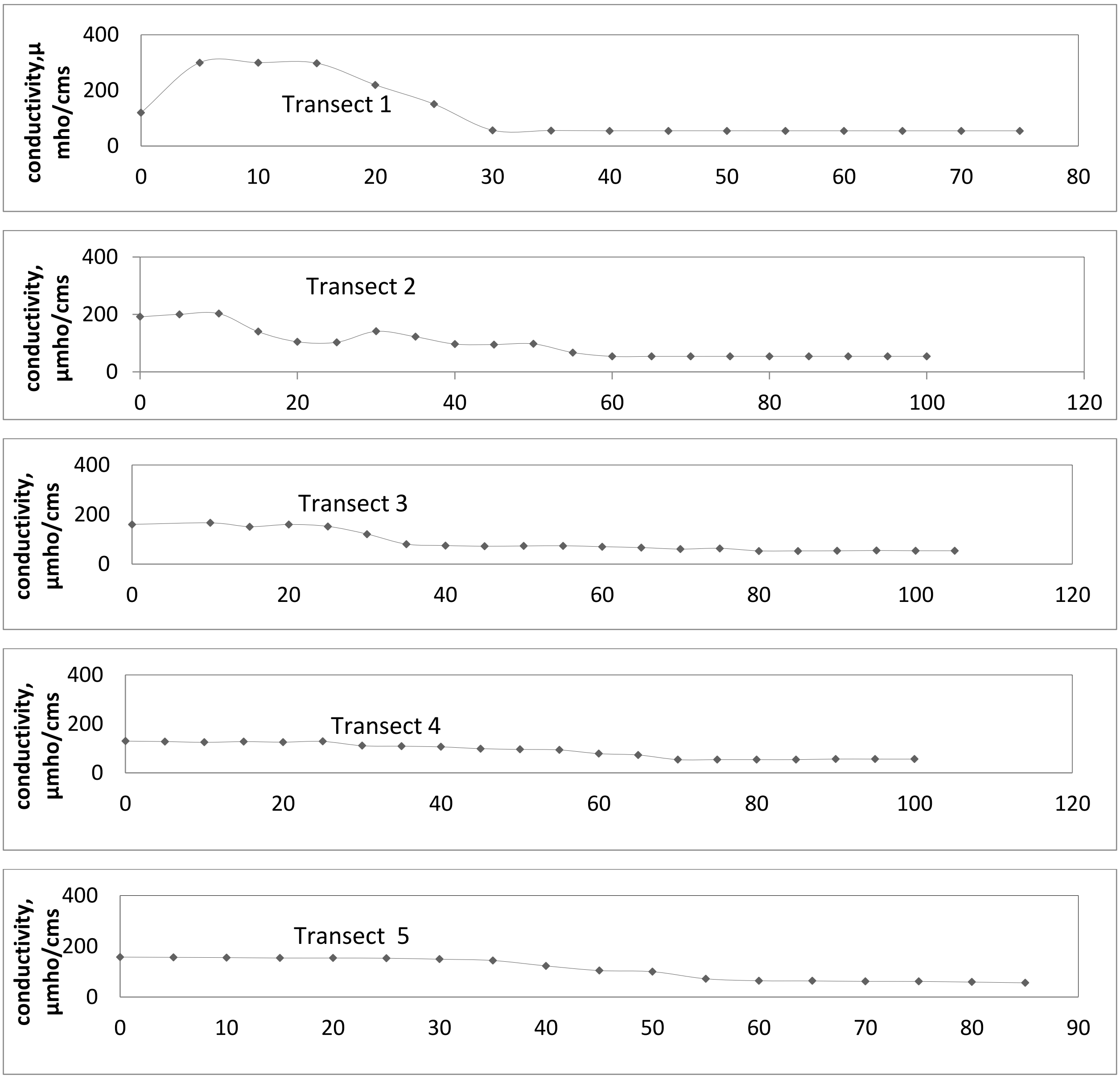
In this work, no tracer element has been used. Conductivity being a natural tracer element, which does not change, has been used as the tracer source. Specific conductance were used to measure the concentrations of dissolved solids (conductivity).

The transverse distributions of conductivity below the outfall at various transects measured are shown in Figure 7. The conductance levels vary at each transect across the river from very low 3 µ mhos/cm to 300 µ mhos/cm. However, the conductivity level is 0 in the middle of the river starting from Transect 1 through

Transect 6, because of the island in the middle of the river. The background conductance in the river water was found to be 25 µ mhos/ cm.

The variations of measured pH and total dissolved solids are shown in Figure 8. It can be seen from the figures that there is significant variation near the shoreline up to a width of 40 m and then on the conductivity values remain constant.

Figure 9 presents the DO variation across the width of the river in the study stretch. The DO values near the outfall shoreline show reduced values up to some width, the cross – sectional values seems to be well above the standard concentration of 4 mg/L at all transects during the survey. However, it can be seen from the figure that there is a region devoid of DO in the width occupied by the small island located in the middle of the river.



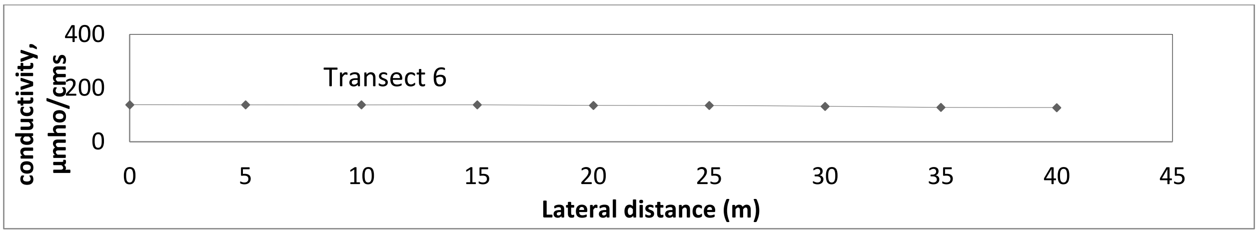


Figure 7: Conductivity Profiles in the Study Stretch of River Kabini

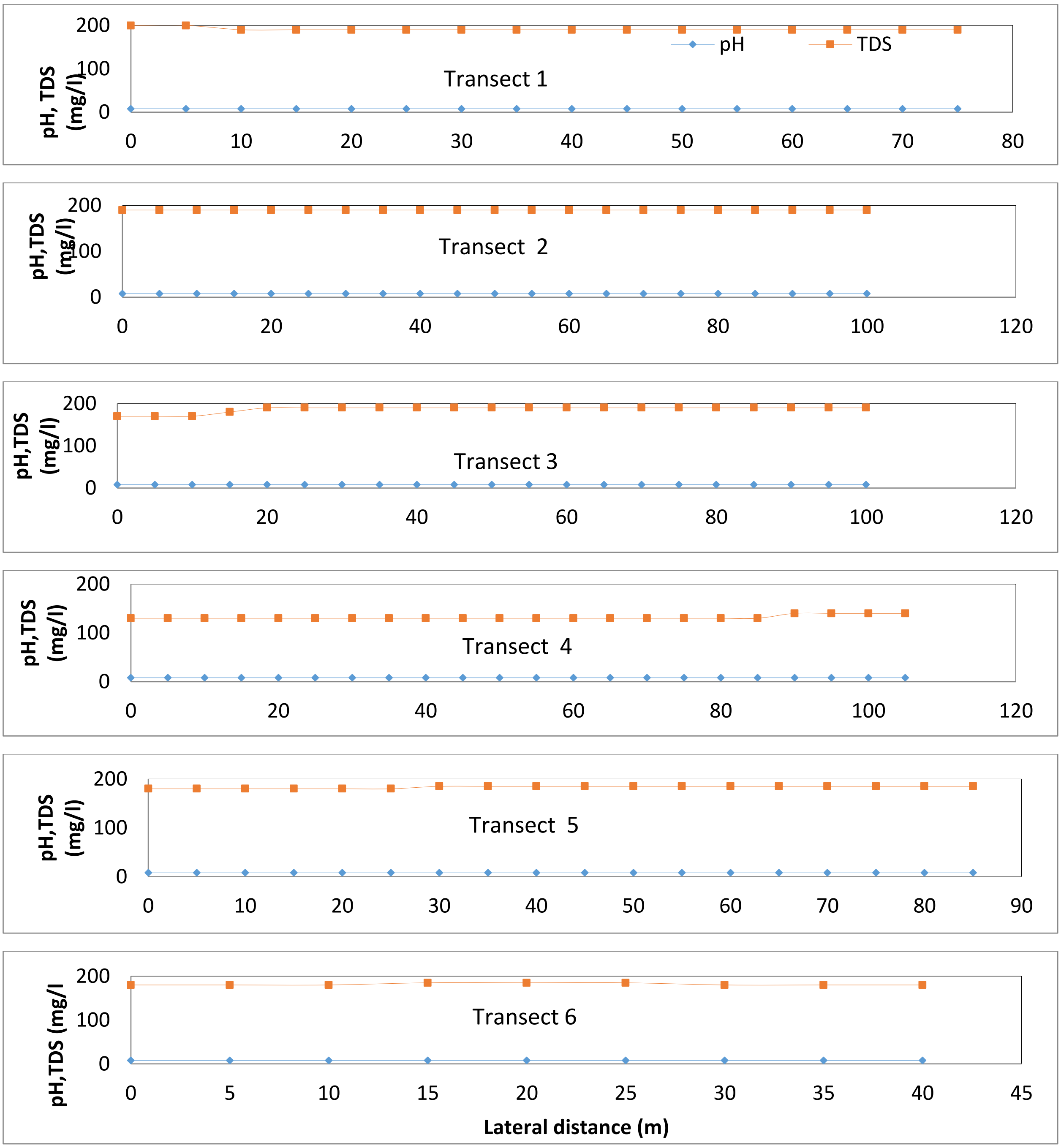


Figure 8: Variations of pH and TDS in the Study Stretch of River Kabini

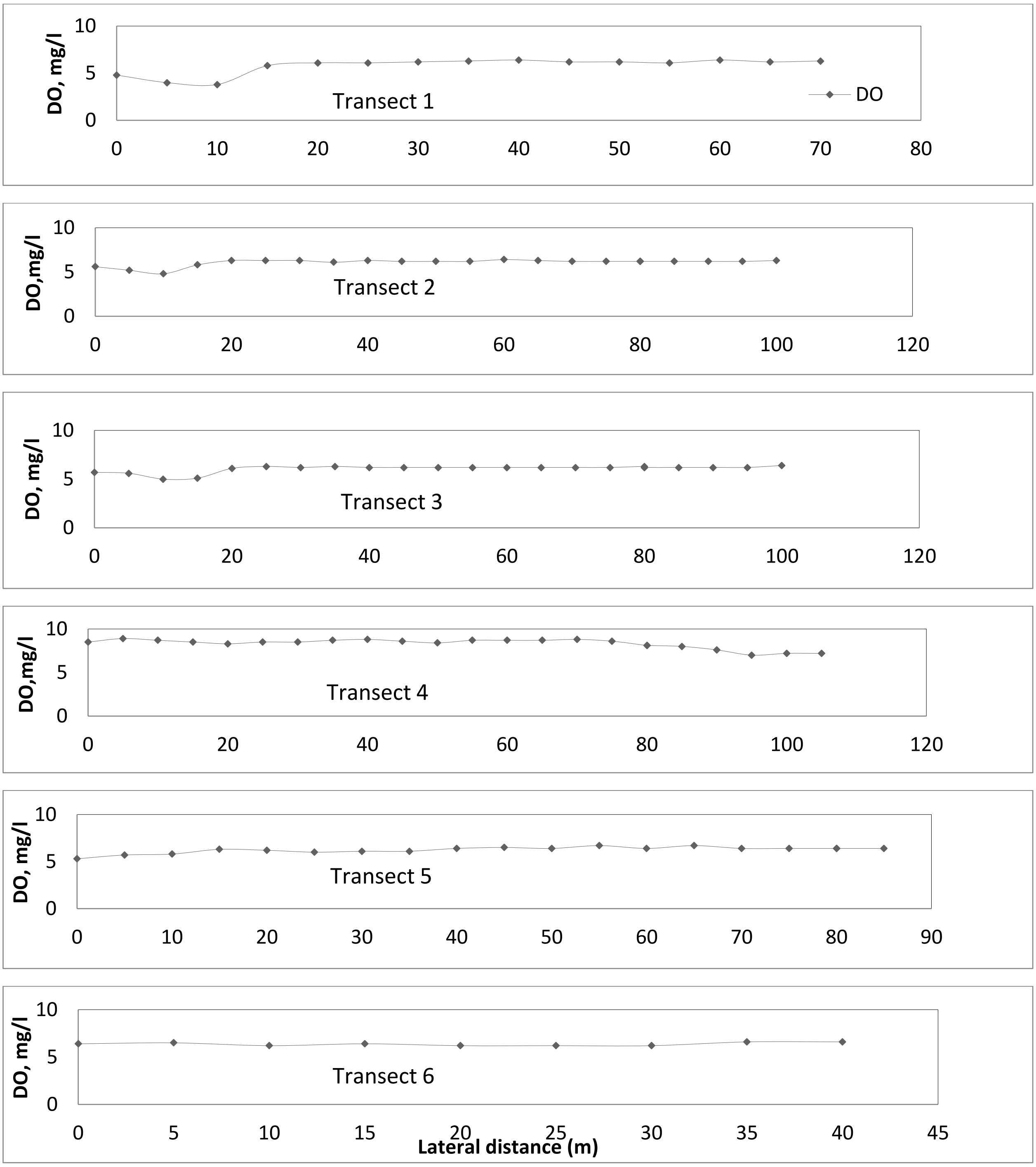


Figure 9: DO Profiles in the Study Stretch of River Kabini

Computer Programs

In this study, the following computer programs have been used to predict the water quality of River Kabini under various scenarios as cited earlier.

MIXANDAT (Mixing Zone Data Analysis Programme)

This programme is used to analyse the data acquired during the field survey at various transects. Cross-sectional sample data for conservative and non-conservative water quality indices, as well as cross-sectional depth and velocity profiles, are used as inputs to this software. Local velocities are simulated at transects when they are not measured by the software. To estimate dispersion characteristics, the output contains mass flux, cross-sectional distributions of flow and concentrations, and variance of conductivity (used as a tracer) distributions. The output also includes average depth, average velocity, shape velocity factor and diffusion factor for each transect. This programme was developed by Gowda in 1980.

Water Quality Model MIXCALBN (Mixing Zone Calibration Model)

This is a pipe outfall-specific version of a water quality prediction model (Halappa Gowda T P, 1980). It's based on a set of mathematical equations that have been tweaked to account for the reach dependence of various factors. This programme can be used for calibration and verification investigations as well as evaluating the effects of management alternatives. Channel width, average depth, mean velocity, background pollutant concentrations, effluent concentrations and flow rate, outfall position with reference to a bank, pollutant decay rates, and non-dimensional transverse diffusion factors are all needed input data. The lateral concentration distribution as a function of cumulative discharge at each transect is included in the output of this model.

MIXPIPOX (Model of Oxygen Prediction for a Pipe outfall)

The MIXPIPOX programme calculates the lateral and longitudinal distributions of CBOD, NOD, and DO in a river channel that receives effluent from a pipe outfall on the bank or in the channel (vertical line source). The following units should be used to represent the data utilised to drive this model.

i) distance in meters

ii) flow rates in cubic meters / second

iii) velocities in meters / sec

iv) temperatures in Celsius degrees

v) decay rates and reaeration rate expressed per sec (base e)

vi) concentration in mg/L or μg/l

vii) transverse diffusion factor (dimensionless)

The following information is necessary to run the above programme.

1. Distance downstream from outfall in meters. Average depth, velocity and width of the river channel at each transect, number of lateral points at each transect.
2. The contaminant being considered.
3. Flow rate in the river just upstream of the outfall.
4. Background concentration of the contaminant and DO.
5. Effluent concentrations of the contaminants and DO.
6. The decay rates of the contaminant and the temperature at which these rates are known.
7. Reaeration rate co-efficient.
8. Temperature of the river water (Design Temperature).
9. Saturation concentration of DO in mg/L.

The above mentioned data are the various input parameters for the MIXPIPOX program except for the location of the pipe outfall at bank or in the river (defined by the partial cumulative discharge, q_S). Further, the program MIXPIPOX calculates the 1-D values, which can be used for comparison between the 1-D model and 2-D model regarding the DO distribution in the river segment.

Data Analysis

Low Flow Analysis

The changes in water quality parameters and the assimilative capacity of a river essentially depend on the flow of the river at any given time and point. Critical water quality conditions occur during low flow periods. Hence, it is essential to conduct low flow analysis to determine the design minimum flow in the river. Generally, for most design works minimum flow having 10-year return period is suggested as a minimum design flow. This analysis is based on universally followed low flow analysis equation of 7Q10 (The low flow in a riverine system which occurs once in 10 years for a minimum period of seven days).

Flow Distribution Curves

The cross-sectional distributions of river flow at several transects are presented, with the distributions normalised for channel width and total river flow. Figure 10 shows non-dimensional graphs q/Q, V/s, and y/B. From the figure, it can be seen that the flows are subjected to variation with respect to width of the river. For example, at Transect 4, 60% of the width carries about 50% of the flow, whereas at Transect 2, 60% of the width carries about 90% of the flow. These cross-sectional variations will have significant implications on water quality in mixing zone and in deciding the location of outfall in the river.

It is feasible to detect the dead zones from the figure shown in Fig 10. The test findings demonstrate that up to 10% of the river flow was stagnant, as well as the occurrence of a water stagnant zone between Y/b = 0.57 and 0.66 on Transect 4. Transect 3, 4 (q/Q = 0.3) had the lowest partial cumulative discharge within 60% of channel width (i.e. Y/b = 0.60) and Transect 2 (q/Q = 0.97).

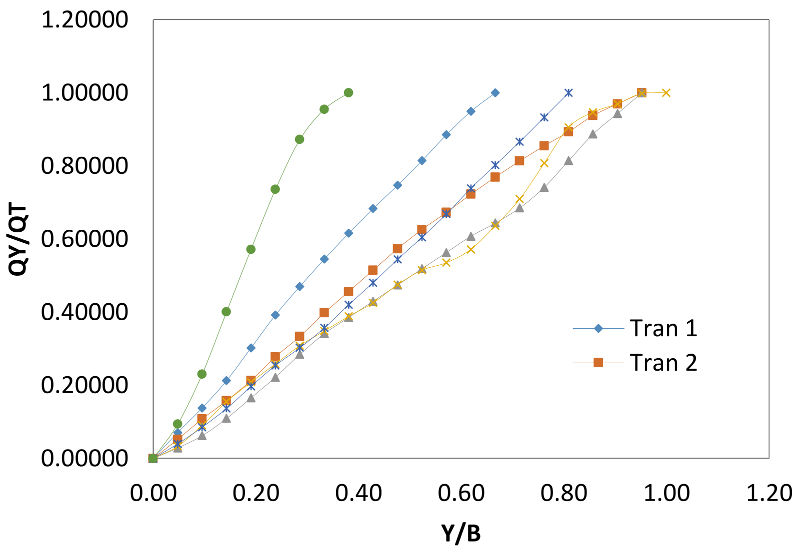


Figure 10: Cross-sectional Flow Distribution Curves of River Kabini

QY = Partial Cumulative Flow from outfall banks

QT = Total Discharge

Y = Distance from Outfall Bank

B = Top Width of Transect

Estimation of Reaeration Rates

The reaeration rates at each transect have been calculated using the O'Connor-Dobbins equation which is given below. The reaeration rates for each transect have been obtained for survey condition.

$$K_a = \frac{(1.34)(D_m u)^{0.5}}{H^{1.5}} \quad \text{... (17)}$$

The reaeration rates at different transects obtained using the above equation are tabulated in Table 1.

Table 1: Estimated Reaeration Rate Coefficients

Transect	1	2	3	4	5	6
Reaeration Rate, day-1	1.397	0.177	1.561	2.414	1.432	0.213

From the table it is seen that the higher values of reaeration rate coefficients were observed at the stretches where the river exhibits free flow and turbulence, whereas the lower values are for the deeper and sluggish water flow segments.

Data Analysis using MIXANDAT Programme

The computer programme MIXANDAT was used to analyse the flow cross-sectional distribution, average depth and velocity values, shape velocity factors, mass flux, and variation at each transect using depths and conductivity values (Halappa Gowda T P, 1980). The summary of these hydraulic parameters and variance values at different transects for the study stretch of River Kabini are given in Table 2.

Table 2: Summary of Hydraulic Parameters and Variance Values

Description	Transect					
	1	2	3	4	5	6
Distance, x (m) from outfall	100	300	500	800	1300	2300
Discharge, Q, (m3/s)	23.260	23.260	23.260	23.260	23.260	23.260
Width,b, (m)	70	105	100	105	85	45
Depth,h,(m)	1.543	1.450	1.388	1.135	1.571	1.631
Velocity,u, (m/s)	0.2010	0.1600	0.1680	0.1950	0.1740	0.3560
Shape Velocity Factor	1.195	1.075	1.118	1.532	1.041	1.262
Variance value,σ2 for conductivity						
Maxi concentration method	88.13	255.15	318.33	662.04	480.92	239.10
Moment method-concentration distribution	819.68	1744.88	1891.29	2283.72	1442.91	516.40
Moment method-Unit Flux Distribution	767.16	1498.06	2118.94	2104.49	1617.64	414.91

The concentration value outside the effluent plume deviated somewhat from the background values in the river just upstream of the outfall, according to the observed conductivity concentration distribution. As a result, the measured distributions were used to determine the background values for each transect. During the investigation, the background conductance values were 25 mhos/ cm. The recovery of the effluent mass flux in the outflow indicates the estimated mass flux of conductance at each transect. The observed differences in conductivity mass flux at various transects could be attributable to water stagnation near the outfall coast.

Estimation of Diffusion Factor

The σ_q^2 values have been determined using conductivity distributions with the aid of MIXANDAT programme. A plot of σ_q^2 / Q^2 versus X/B has been prepared and is shown in the Figure 11. From this plot the obtained slope is equal to twice the value of β, from which the value of β obtained as 0.0013137. This value of β is used in the calibration of model. The computer outputs of MIXANDAT include mass flux of conductivity.

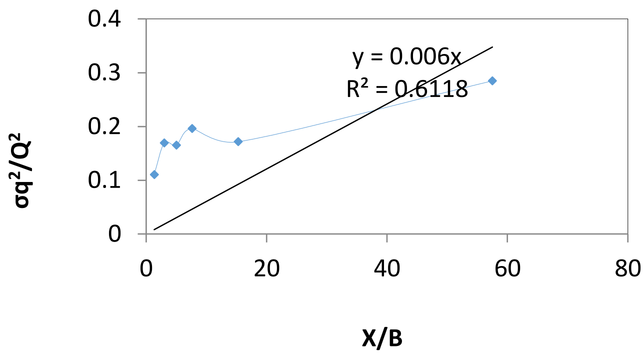


Figure 11: Plot of σ_q^2 / Q^2 versus X/B

Conclusions

The following conclusions are derived from the study:

- Extensive monitoring of water quality parameters were carried out. These indicate variability in lateral as well as longitudinal directions. In order to account for these variations, mixing zone concept has been adopted.
- Concentration gradients of various water quality parameters including conductivity, BOD_5 and DO were observed under survey conditions. The DO values were found to be in compliance with the guideline value of 4 mg/L.
- The DO values were predicted using MIXPIPOX programme and the values were found to agree very well with the measured DO concentrations.
- The validated model was used for DO predictions under various engineering options such as discharge of raw wastewater, discharge of primary treated effluent, discharge of secondary treated effluent under survey flow conditions.
- Under survey flow condition option, the discharge of raw wastewater would result in DO values of around 4 mg/L for a short distance downstream of the outfall while, for other options the guideline value is met at all transects.
- The location of the outfall in the river has been considered at 30%, 40% and 50% of river flow to predict the DO concentrations for all the options namely, raw effluent, and primary and secondary

treatment under survey flow conditions. The predictions indicate that the DO values under survey flow condition comply with the guideline value of 4 mg/L.

References

A. John Veil. 1994. Impact of a 1000-foot thermal mixing zone on the steam electric power industry Environmental Assessment Division Argonne National Laboratory, Chicago University.

Barik, Swarup, and D. C. Dalal. 2018. Transverse concentration distribution in an open channel flow with bed absorption: A multi-scale approach Communications in Nonlinear Science and Numerical Simulation. 65: 1-19. doi:10.1016/j.cnsns.2018.04.024

Beltaos. S. 1979. Transverse Mixing in Natural Streams, Canadian Journal of Civil Engineering. 6(4): 575-591. https://doi.org/10.1139/l79-070

Bhargava. D. S. 1986. DO Sag Model for Extremely Fast River Purification. Journal of Environmental Engineering Division, ASCE. 112(3): 572-585.

Covar. A. 1976. Selecting the Proper Reaeration Coefficient for use in Water Quality Models. Proceeding of the USEPA Conference on Environmental Modeling and Simulation. Cincinatti, Ohio.

Cox. B.A. 2003. A review of Dissolved Oxygen Modelling Techniques for Lowland Rivers. An International Journal for Science Research into the Environment and its Relationship with Man. 303-334. https://doi.org/10.1016/s0048-9697(03)00062-7

David A. Todd, and B. Philip Bendient. 1985. Stream DO Analysis and Control. Journal of Environmental Engg, ASCE. 111(3): 36-352. https://doi.org/10.1061/(ASCE)0733-9372(1985)111:3(336)

Doneker, R. L., G.H. Jirka. 1991. Expert system for mixing zone analysis and design of pollution discharges. Journal of Water Resource Planning Manage. 117 (6): 679-697. https://doi.org/10.1016/j.aej.2012.12.003

Eheart. W. J. 1990. Methods for Distinguishing Between Single and Multiple Discharge Situations. Journal of Water Resources Planning and Management. 116(3): 335-348. DOI: 10.1061/(asce)0733-9496(1990)116:3(335)

Halappa Gowda. T. P. 1980. Stream Tube Model for water Quality Prediction in Mixing Zones in Shallow River. water resources Branch, Ontario Ministry of Environment, Toronto, Canada. 14.

Halappa Gowda. T. P. 1983. Modelling Nitrification Effects on the Dissolved Oxygen Regime of the Speed River. 17(12): 1917-1927.

Halappa Gowda. T. P. 1984. Critical point Method for Mixing Zones in Rivers. Journal of Environmental engineering Division (USA), ASCE. 110(EE1): 244-262.

http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCAL82X0068448

Jirka, G. H., R.L. Doneker, and S.W. Hinton. 1996. User's manual for CORMIX3: A hydrodynamic mixing zone model and decision support system for pollutant discharges into surface water, EAP, Washington, DC.

Mirosław Skorbiłowicz, Elżbieta Skorbiłowicz, Paulina Wojtowicz, Emilia Zamojska. 2017. Determination Of Mixing Zones For Wastewater With Receiver Waters. Journal of Ecological Engineering. 18(4): 192–198. http://dx.doi.org/10.12911/22998993/74291

Rankovic. V., J. Radulovic, I. Radojevic, A. Ostojic, and L. Comic. 2010. Neural network modelling of dissolved oxygen in the Gruza reservoir, Serbia, Ecological Modelling. 221(8): 1239–1244. http://dx.doi.org/10.1016/j.ecolmodel.2009.12.023

Skowysz A. 2011. On the use of empirical formulas for calculating the length of the full path of mixing waste water discharged into rivers and canals. Scientific Review Engineering and Environmental Shaping. 53: 237–246. https://doi.org/10.12911/22998993/74291

Stephen P. Schreiner, Theresa A. Krebs, Donald E. Strebel, Allison Brindley, and Cyrus G. Mccall. 1999. Validation of the cormix model using thermal plume data from four Maryland power plants, The Maryland Department of Natural Resources, powerplant research program. Columbia. 114

U. S. Geological Survey.582-c:19.

US New England, Inc. 2002. Thermal Discharge Mixing Zone Recommendation, Brayton Point Station, Somerset, Massachusetts, Massachusetts Department of Environmental Protection.

Water Quality Standards Handbooks. EPA,2014.

Yotsukura, N., and E. D. Cobb. 1972. Transverse Diffusion of Solutes in Natural Streams.