WATER QUALITY MODELING OF THE KALI RIVER, INDIA

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Abstract. Water quality monitoring procedures effective in calibrating the QUAL2E model for the Kali River in India are described. The stability of dry season conditions for the Kali River are utilized to consider the migration pathways, and hence the calibration efforts necessary for water quality models. Alternative procedures for calibrating values for the reaction rates are utilized for reinforcement of the findings. These alternatives include changes in stream turbidity which are shown to be a useful measure of benthic oxygen demand. Ratios of BOD_5 to COD are reported between sugar mills, industrial inputs and municipal sources.

Key words: BOD modeling, India, QUAL2E, sediment oxygen demand, water quality

1. Introduction

Disposal of wastewater generated from municipal and industrial sources with little to no treatment prior to discharge is common practice in many developing countries. This practice has been continuing over the history of civilization but as a result of population growth and increasing industrialization, serious problems of water quality are commonplace. Although undesirable, the existence of the water quality problems in developing countries is very much the consequence of the economic productivity focus and avoidance of the expenses in the collection and treatment of wastewater. The implications of the deteriorating quality of the receiving waters are considerable both in the immediate situation and over the longer term. The discharges from densely-inhabited regions in many situations have transformed a freshwater stream into an open sewer. The case of the Kali River water quality in India, as described in this paper, is just such an example.

Information available on river water quality in India, as is the situation for many other developing countries, is very limited. Limited monitoring efforts precipitate the need for considerable judgement and extrapolation of information from the published technical literature for use in formulating mathematical models for such situations. Problems in defining such features as pollutant loadings, instream reaction coefficients, and benthic oxygen demands are indicative of the considerable difficulty in using computer models such as QUAL2E. The characterization of the mathematics to describe the processes is well accepted; the input data requirements for these models is the challenge. A case study application to the Kali River, India is a demonstration of some of the difficulties. However, several features relevant to such water quality models are shown to make certain aspects of the water quality

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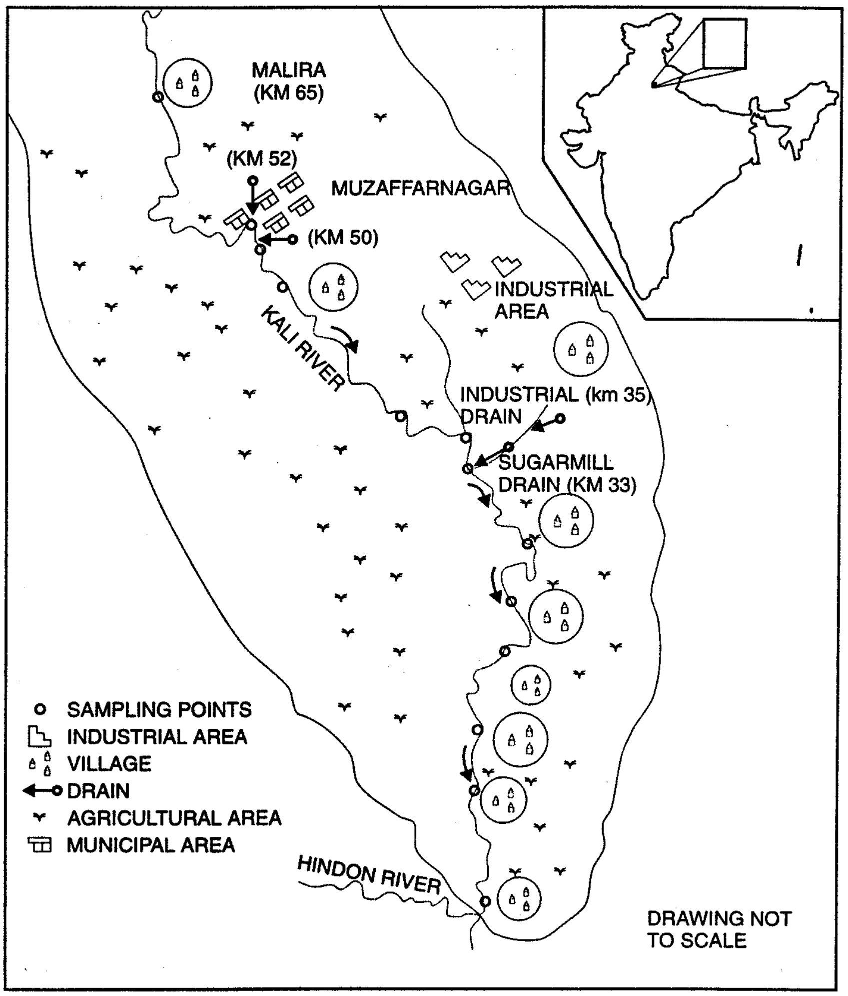

Figure 1. Index map of study stretch (Kali River).

modeling in India to be a simpler task than comparable modeling efforts carried out, for example, in North America.

2. Description of the Study Area

2.1. GEOGRAPHICAL AND HYDROLOGIC FEATURES

The study of water quality of the Kali River is limited to the lower stretch of the River for 65 kilometers starting from Malira bridge located 10 km upstream of Muzaffarnagar City, Uttar Pradesh, India down to the confluence of the river with

Table I
Average Monthly Rainfall in Region of the Kali River, India

Month	Rainfall (mm)
January	15
February	12
March	8
April	5
May	9
June	75
July	255
August	239
September	135
October	187
November	7
December	7

the Hindon River (shown in the index map in Figure 1). The Kali River is a tributary of the Hindon River which again is a tributary of the Yamuna River, and eventually flows into the Ganga River. Geographically, the river basin is located with latitude of $29^\circ 13' – 30^\circ$ N and longitude of $77^\circ 32'$ - $77^\circ 4'$ E. The River drainage area covers approximately 750 km^2 with a travel length of about 150 km. Despite its origin in the plains of the Himalayas and considerable drainage area, the Kali does not contribute significant flow into the Hindon River. The dry season flow (November to February) varies from 3.60 $m^3\ s^{-1}$ to 3.76 $m^3\ s^{-1}$ near Malira bridge (at top of Figure 1) and increases to 7.25 $m^3\ s^{-1}$ to 7.40 $m^3\ s^{-1}$ just prior to the confluence with the Hindon (at bottom of Figure 1).

The minimal variability of the flows over time throughout the dry season, as noted by the ranges in flows noted above, is highly relevant to water quality modeling, namely that steady-state flow assumptions as implicit within many computer models, are very appropriate throughout the travel time down these rivers. Average rainfall at the nearby meteorological station on the Hindon River is listed in Table I and the minimal rainfall for the months of November to May is readily apparent. The monsoon period usually continues for four months, from June/July to October. Table 1 indicates the average monthly rainfall for the 10 year period (1984 to 1994) collected from nearby meteorological stations.

The rainfall pattern removes some of the difficulty in mathematical modeling since only two seasonal flow patterns occur (wet and dry). It also greatly simplifies the planning for data collection efforts since the sampling program is not likely going to be disrupted by incident rainfall, causing variable flows during the sampling. The major task of trying to sample during relatively low flow periods and then extrapolate to extreme conditions such as the seven day 10 year low flow, as is the common practice in North America, is thus avoided.

Equally important to the modeling of water quality during the dry season in India is that much of the Kali River flow throughout the dry season is contributed to the River via bank recharge from flood irrigation of adjacent fields. In other words, during the dry season the nonpoint source loadings to the River must be in dissolved form since the transport pathway is groundwater recharge to the stream with no surficial drainage. Of the Kali River flow of 7.33 $m^3\ s^{-1}$ (average), about 19% (1.37 $m^3\ s^{-1}$) is contributed by the four point source discharges located in and around Muzaffarnagar but these contributions are easily identifiable from the municipal drains. The remaining 81% of the Kali River inflows occur via groundwater flux to the River.

Alternatively, during the monsoon period, the Kali River flow increases to a level approximately 10 to 12 times higher than the dry season flow and floods into the overbanks in many stretches. Rainfall contributions flow overland during the monsoon period and through small line channels (locally known as nala). The overland flow pathway during the rainy season provides the additional pathway of surface movement of water and pollutants involving scour and erosion.

The ambient atmospheric temperature in the River basin area goes down to a minimum of 3 – 4 °C during the winter (night-time) and during the summer the air temperature increases to a high of 42 – 44 °C (day-time). However, since the River flows during the dry season arise from groundwater recharge to the stream, the variations in the stream temperatures are much less in magnitude than the air temperature. The stream temperatures are relatively constant at approximately 17 to 20 °C (in the absence of significant municipal and industrial loads).

2.2. LAND USES AND SOCIO-ECONOMIC ASPECTS

The drainage area in the Kali River basin is primarily in agricultural production, with the exception of Muzaffarnagar City with a population in the order of 0.45 million. Muzaffarnagar contains a large number of small and medium scale industries such as steel rolling mills, and chemical factories. Dairy and sugar mill factories in and around the city have contributory roles in shaping the urban economy. In addition to this city, two small towns (with populations between 25 000 and 50 000) are located in the vicinity of the study reach and seven villages (populations between 2000 and 5000) are situated on the banks of the River within the study reach, as noted in Figure 1. Agricultural production is the backbone of the economy of the villages. Crops that are produced from agricultural fields include: sugar cane, wheat, and a variety of winter and summer vegetables. Water for irrigation of agricultural fields is drawn partly from the nearby Upper Ganga Canal and partly from ground water sources. The villagers indicated that Kali River water was in use for irrigation and other routine uses (except drinking) prior to the introduction of industrial wastewater into the Kali River. As well, the catching of fish was one of the routine jobs of villagers. However, following the introduction of industrial wastewater inputs, all of these direct beneficial uses downstream of the industrial emissions have ceased. Current uses of water include: the washing of clothes by professional laundry men, the bathing of domestic animals, the washing of vegetables before bringing them to market, and in some places the River serves as a place for sanctuary of migrating birds. The domestic needs for water in Muzaffarnagar and in the small towns are met from ground water sources while for villages it is met through shallow tube wells.

2.3. ENVIRONMENTAL ASPECTS

Muzaffarnagar has an open drain sewer system through which municipal wastewaters are discharged into the Kali River at two locations. The drains probably originated as natural storm runoff channels. With the growth of the population, the stormwater drains also served as sullage drains and thus are very evident as primary contributions of wastewater to the River. One drain discharges approximately 12 000 m^3 day^{-1} at 52 River Kilometer (Rkm, where Rkm indicates the frame of reference along the River as noted in Figure 1) and the second of 14000 m^3 day^{-1} at 49.75 Rkm. Industries located in and around the City mostly discharge their liquid wastes into an industrial drain, without any preliminary treatment, which joins the river at 35.0 Rkm. The daily average flow of industrial wastewater at 35 Rkm is 48 000 m^3 day^{-1}. At 33.25 Rkm is another industrial drain carrying raw wastewater from sugar mill factories with an average flow rate of about 15 000 m^3 day^{-1}. There is no organized sewer system for small towns and villages. Wastewater generated from these areas is drained out to the nearby agricultural lands where it then infiltrates and/or evaporates.

2.4. MONITORING TECHNIQUES

There are no permanent monitoring stations nor any baseline data available to give a preliminary indication of pollution concentrations prevailing in the Kali River, a situation representative of most rivers in India. The collection of samples and in-situ measurement of specific water quality constituents and river hydraulic parameters, over a distance of about 50 km, is the only option left for studying the river water quality. The constancy of conditions (flow and pollutants) throughout the dry season, make the data collection and subsequent modeling task simple.

In addition to the monitoring of the four point sources, samples of river water quality constituents were collected and analyzed for 13 different locations (as shown in Figure 1) along the Kali River. Water quality constituents were measured at the monitoring sites, and as needed, in the laboratory, for BOD_5 (5-day Biochemical Oxygen Demand), DO (Dissolved Oxygen), COD (Chemical Oxygen Demand), Temperature, Solids (suspended and settleable), pH, and TDS (Total Dissolved Solids). River hydraulic parameters for velocity and depth were measured at four

Table II
Listing of laboratory-measured benthic oxygen demand

River Location (Rkm)	Benthic Oxygen Demand (g/m^2 day^{-1})
49.75	7.50 ± 0.20
42	6.00 ± 0.25
35	2.5 ± 0.15
33.25	1.75 ± 0.10

different locations, respectively at 65 Rkm, 52.5 Rkm, 36 Rkm, and 32 Rkm. The variation of depth of water in the River for a single location typically changed from 0.50 meters to 1.10 meters across the River, allowing measurement of hydraulic parameters at two metre intervals across the River by walking. For the places where access from bridges was available, river water depths were measured from these. Average stream velocity was calculated using the average of velocities observed at 0.2 d and 0.8 d (where d = depth of water at any flow location). The discharges from the point sources were calculated using the velocity and cross-sectional area. River water samples for water quality analyses were collected from three locations, at 1/3, 1/2 and 2/3 of the surface width and from places where river water appeared to be completely mixed to decrease the sampling effort.

The BOD$_5$ settling rate is usually more pronounced in the vicinity of outfalls and decreases downstream. Initial estimates of the instream settling rates were obtained from percentage transmission (a measurement of turbidity) in water between two known locations whose average stream velocities and distance between them are known. The velocities and distance were then used to estimate travel time and the percentage reduction of transmission of light measured at the same depth of water indicates the settling rate of the organic matter. Mathematically, this was determined from

$$k_s = (P_1 - P_2)/t$$

where $t = x/(V_1 + V_2)/2$ where x is distance between two points, V_1 and V_2 represent the average stream velocities at the two locations, P_1 = % transmission at point 1, and P_2 = % transmission at point 2. However, the final estimate of settling rate was made from the difference of total removal rate (k_r) and the deoxygenation rate coefficient (k_d).

Measurements of the oxygen demand for benthos were obtained by collecting bottom samples from the vicinity of the four outfalls and upstream of the municipal drain at 52 Rkm and analyzing them in the laboratory to quantify the oxygen demand. River bottom soils were collected by a 5 cm diameter sampling device and placed in air-saturated water. The depletion of dissolved oxygen over different days was measured with the results as listed in Table II. The values obtained were used to estimate the oxygen uptake per unit area. It is noteworthy that the dramatically-increased flows during the rainy season flush out the bottom deposits each year. Thus, it is not expected that bottom sediment oxygen demands are an overyear phenomena, a useful realization for design of future sampling programs for model calibration.

Standard methods (APHE, 1985) were followed in the analysis of water samples in the laboratory. Meteorological data for ambient temperature, wind velocity, cloudiness factor, dry and wet bulb temperature as required by the model calibration to the water quality measurement pertinent to the day the data were collected from nearby meteorological stations.

2.5. QUAL2E MODEL

The enhanced stream water quality model, QUAL2E (Brown and Barnwell, 1987) permits the simulation of several water quality constituents in a one-dimensional branching stream system. The finite difference solution to the one-dimensional advective-dispersive mass transport and reaction equation for steady flow has been used as the mathematical tool in model formulation. The QUAL series of computer programs have a lengthy history in systems analysis in water quality management since its first release by the Texas Water Development Board as QUAL-1 (TWDB,1970) until its enhanced version QUAL2E (NCASI,1985). In addition to the QUAL series, many steady-state water quality models are available but in an evaluation study the QUAL2E model has been ranked as the best one-dimensional steady-state model (McCutcheon, 1985).

2.6. MODEL CALIBRATION

2.6.1. *Discretization of River Reach*

The total study length of 65 km from Malira bridge down to the confluence of the river with the Hindon River was discretized into 15 reaches with computational element lengths of 0.25 km each and in accordance with the QUAL2E requirements.

2.6.2. *Hydraulic Data*

The dry season flows and river geometry measured on several dates of December-February, 1994/95 provided the base data to estimate the coefficients and exponents of velocity and depth. It was observed that the fluctuation of river flows during the dry season was minimal as noted previously.

For an assumed value of Manning’s roughness coefficients (range used n = 0.025 to 0.035), the energy gradient slope was computed using Manning’s equation from the field-measured hydraulic data. Using different depths of flow, velocity and flow rate, these data were utilized to estimate the coefficient and exponent of velocity and depth for different reaches with the results as listed in Table III. The difference of flow (outflow from reach – upstream inflow – identified point source discharge)

Table III

River flow and hydraulic data

River Location (km)	Flow ($m^3\ s^{-1}$)	Incremental Flow ($m^3\ s^{-1}\ km^{-1}$)	Velocity		Depth	
			Coeff.	Exp.	Coeff.	Exp.
65.0–52.0	3.68–4.42	0.057	0.178	0.333	0.358	0.48
52.0–49.75	4.42–4.85	0.057	0.154	0.300	0.474	0.395
49.75–35.0	4.85–6.36	0.090	0.239	0.294	0.436	0.395
35.0–0.0	6.36–7.30	–	0.172	0.350	0.322	0.488

Table IV

Reaction kinetic coefficients from instream measurement

River Stretch	k_d (l day^{-1})		k_g (l day^{-1})		k_o (gm $m^{-2}\ day^{-1}$)	
	Instream	Calib.	Instream	Calib.	Instream	Calib.
65.0–52.0	–	0.1–0.23	–	–	0.0–6.0	0.5–6.0
52.0–49.75	–	0.40	1.65 (±0.03)	1.25	6.0 (±0.25)	6.5
49.75–35.00	0.25 (±0.05)	0.5–0.25	1.85 (±0.03)	1.50–0.0	7.50 (±0.25)	7.50
35.0–33.0	–	0.65	3.25 (±0.07)	3.00	1.75 (±0.10)	1.50
33.0–0.0	0.30 (±0.10)	0.85–0.30	5.85 (±0.01)	5.5–0.0	2.5 (±0.15)	2.0

observed at two locations is considered uniformly distributed and input to the model as incremental flow.

2.6.3. *Carbonaceous Deoxygenation Rate Coefficient (k_d)*

River water quality samples collected on different dates from the 13 different locations have been analyzed in the laboratory for determination of BOD_5 from 20 °C to the river water temperature using the standard Arrhenius temperature-correction equation. The slopes of semilog plots between BOD_5 at river temperature (log scale) and travel time (linear scale) give the requisite instream rate coefficient. Because of the high values for the settling rate coefficient and sediment oxygen demand (SOD) mainly in the vicinity of the point sources, k_d varies from reach to reach (where k_d = instream deoxygenation coefficient at 20 C STP). The values of k_d are more pronounced after the point inputs and reach a stable value as pollutants move downstream and the organic matter has settled. These situations were observed between Rkm 49.75 to Rkm 35 and Rkm 33 to Rkm 0. The mean values of instream rate coefficients and their range of variation obtained from semilog plots for these stretches are given in Table IV.

In a study of instream deoxygenation rate prediction, Wright and McDonnell (as reported in Laramie *et al.*, 1989) proposed the following predictive equation

$$k_d = 10.3Q^{-0.49}$$

where Q = steady-state stream flow (ft^3 s^{-1}). The Wright and McDonnell equation was used to assign the initial values in places where stability of the instream BOD decay was not observed, such as between the stretches Rkm 52 to Rkm 49.75 and Rkm 35 to Rkm 33. Initial values of 0.854 and 0.70 were estimated for the known flow conditions whereas the calibrated values to the observed DO profiles are 0.4 and 0.65 (Table IV) respectively.

2.6.4. *Reaeration Rate Coefficient (k_2)*

QUAL2E offers 8 options for estimating or reading in the reaeration rate coefficient. These options include expressions derived by Churchill *et al.* (1962), O'Connor *et al.* (1958), Owens *et al.* (1964), and Langbien *et al.* (1967) which are all in terms of depth and velocity. Of these alternative equations, the Owens et al. formulation was derived for conditions similar to the prevailing conditions in the Kali River. It was developed for streams exhibiting depths of 0.4 to 11.0 ft and velocities of 0.1 to 5.0 ft s^{-1}, and for the Kali the depth range is 2.5 ft to 3.5 ft and velocity range of 1 to 1.25 ft s^{-1}.

At river kilometer 50 i.e. after the first point source input, the river water crosses over a weir of 0.63 m that creates an appreciable reaeration effect used in the model calibration.

2.6.5. *Settling Rate (k_s) and Sediment Oxygen Demand (k_o)*

Raw wastewater is discharged to the Kali River. The relatively high velocities in the wastewater drains transport the organic matter to the outfalls but the substantial reduction in velocity as the point source contributions join the River causes the suspended matter to settle out. These organic matter deposits replenish the sediment oxygen demand throughout the dry season. River bottom soils are more loamy in the vicinity of municipal drains while after the industrial drains they are more sandy and black in color.

Values of reaction kinetics for SOD (see Table II) represent the final values with their range of variation estimated from the calibration of the QUAL2E model to the field-measured quality for the Kali River. Only the reaeration coefficient was determined from external calculations. The values for k_d, k_s and k_o with their range of variation as given in Table IV obtained from instream measurements were used for calibration of the model. The final values were determined by performing sensitivity assessments of the parameters.

2.6.6. *Pollution Loads*

Pollutant constituents of headwater flow and the four point loads have been measured and values used for calibration of the model are listed in Table V. The

Table V

Constituents concentration of inputs loads

Description	Flow ($m^3\ s^{-1}$)	Temp (°C)	BOD_5 (mg L^{-1})	DO (mg L^{-1})
Headwaters	3.68 ±.08	17	5.95±.5	7.6±.3
Municipal Drain(Rkm 52)	0.30 ±0.03	18	325 ±5.	0.0
Municipal Drain(Rkm 49.75)	0.35 ±.03	18.5	318 ±5.	0.0
Industrial Drain(Rkm 35)	0.55 ±.02	21.5	801.±10.	0.0
Sugar Mill	0.166±.02	26.5	1695 ±15	0.0

variations of values around the mean represent the deviation of the parameters estimated from sampling on two different occasions in 1994/95. The constituent concentrations in the incremental flows are assumed similar to the headwater constituents since there are no upstream point sources of the Malira bridge.

3. Analysis of Results and Discussion

The QUAL2E model was run with one set of observed data set and subsequently validated with a second set of field data (see Figure 2). While calibrating the input data sets, attention has been given to adjust the assumed values that have been considered from the available literature. Since the response of pollution loads are mainly governed by the reaction coefficients of respective constituents that are influenced by the river hydraulic conditions, adjustments of values were focused on the reaction coefficients. Sensitivity options employed in the model provided the requisite tool to choose the extent to which reaction coefficients were adjusted.

Figures 2(a) and (b) show the computed concentration profiles and observed values of BOD_5 and DO along the Kali River. The relative similarity of the observed values for the two different sampling periods is apparent from the proximity of the data points. Figures 2(a) and (b) show a good match between computed and measured values of BOD_5 and DO. It is interesting to note from Figure 2(a) that concentrations of BOD_5 fall sharply after the point source discharges and decrease at the rate of deoxygenation rate coefficient as one proceeds downstream (as per the higher settling rate coefficient in the vicinity of the various outfalls). The DO profile (Figure 2(b) clearly shows two distinct DO sags, one in between the municipal drains and industrial drain at 45 Rkm, has a minimum DO concentration of 0.75 mg L^{-1} (a 6.85 mg L^{-1} depletion from the headwaters DO of 7.6 mg L^{-1}. Another DO sag is just after the industrial drain with a ‘zero’ DO value continuing for a stretch of about 22 km. This River stretch is anaerobic. The DO recovers

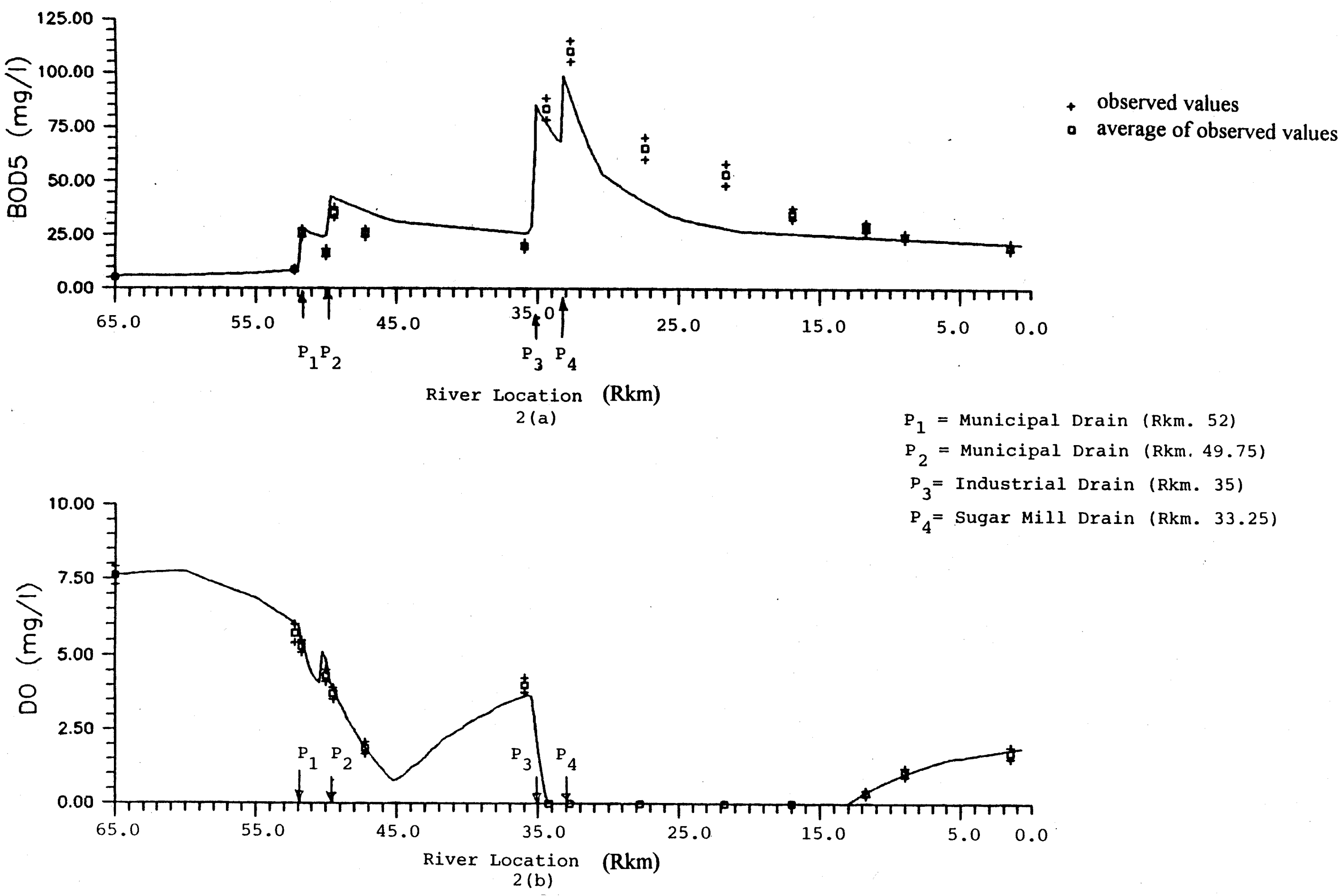

Figure 2. Observed and predicted CBOD5 and DO concentration.

downstream after 13 Rkm and reaches a maximum value of 2.0 mg L^{-1} before mixing with the Hindon River. The respective value of BOD_5 is estimated to be on the order of 25.0 mg L^{-1} which mixes with the Hindon River water with a BOD_5 of 2.0 mg L^{-1}. At 50 Rkm there is a sharp aeration or increase of DO level (a 28% gain measured over the location-specific DO) due to the existence of the weir. Upstream of the municipal drain at 52 Rkm, the DO deficit is approximately 2.1 mg L^{-1}. This ‘background’ deficit is due to diffuse upstream sources and the sediment oxygen demand in this region in which laboratory results indicated a magnitude of 6.0 g/m^2 day^{-1}.

pH of the river water ranged from 6.9 to 8.0 and is well within acceptable limits, with tendencies toward alkalinity as one proceeds downstream. The ratios of BOD_5 to COD for municipal (0.85), industrial (0.48) and sugar mill (0.55) were measured. These results indicate that municipal wastewaters are more biologically degradable within the 5day period than are the industrial and sugar mill wastewaters.

4. Conclusions

The steady-state water quality model QUAL2E has been applied to the problem of modeling of the Kali River water quality (dry season flow). Data limitations are the primary difficulty associated with use of the model for applications to rivers such as the Kali River. However, careful delineation of migration pathways allows effective and focussed data collection efforts and calibration of the model.

In addition to providing the management ability to the water quality, QUAL2E can be used as a good tool for determining reaction kinetics of a river facing problems of water quality that leads to the ability to assess the waste assimilative capacity of a river.

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