Fecal Coliform Management Using a Coupled Hydrodynamics and Water Quality Model for the River Ravi in Pakistan

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Abstract

A Fecal Coliform (FC) management framework is developed incorporating segmentation of river reaches, hydrodynamic and water quality models and FC management under critical winter low flow conditions for a highly polluted River Ravi. FC die-off rate in the river is determined from a field survey of a selected river reach. The travel time calculated with the help of a hydrodynamic model is 0.25 days in the selected reach. FC die-off rate (K_b) was found to be 1.2 day^{-1} at 20^{o}C. Model calibration with monitoring data set reveals reasonable agreement of the simulation results with the measured field values under low flow conditions. Presently, the river is receiving raw wastewater and the simulation results shows very high fecal coliform levels up to 100x10^{6} MPN/100mL in the river water. These levels are much higher than the required recreation and irrigation standards. Simulations are carried out to assess water quality for the future fecal pollution loads in year 2025 and the results reveal that up to 6 log reduction in FC is required at the wastewater outfalls, whereas, 5 log reduction would be sufficient for surface drains to meet desired FC standards under low flow conditions.

Key Words: Water Quality Management, Fecal Coliform Modeling, Bacterial Pollution, Rivers water quality, Irrigation Water Quality

1. Introduction

Bacterial contamination is the oldest of all water pollution problems and was manifested by identifying the linkage between the contaminated water and disease transmission. The problems associated with fecal contamination are still growing particularly in developing countries with discharge of untreated effluent from domestic sources into surface waters. Due to these increasing trends in fecal contamination of rivers, water quality problems have increased to such levels that most of the uses including drinking, bathing, irrigation and recreation have been effected or in certain cases eliminated completely. Total coliform (TC) is a group of bacteria found in polluted and non-polluted soils, humans feces and other warm blooded animals (Thomann & Mueller 1987). The fecal coliform (FC) is a sub group of TC and their presence indicates the organisms from the humans and animals intestinal tracts. Fecal coliforms are preferred on TC as their origin could not be the soil organisms (Chapra 1997). About 2 x 10^{9} FC can be excreted by one person in a day (Chapra 1997).

The Ravi River is one of the most polluted large rivers in Pakistan. The study reach of the river is a stretch of about 98Km located between the Ravi Siphon to Balloki Headworks (846800N & 3355200E and 788400N & 3300500E). The river is presently receiving municipal and industrial wastewaters through five city outfalls and two large surface drains from the city of Lahore (Fig 1). As a result, the river is facing serious water quality problems related to high fecal contamination, low dissolved oxygen and un-ionized ammonia (Haider 2010). Moreover, the river flows are extremely variable (less than 10 m^{3}/s - 10,000 m^{3}/s) (Fig 2). During minimum flow conditions, the water quality problems are high and the river is unable to meet the required water quality standards for most of its beneficial uses (i.e., agriculture, water supply, fish and recreation).

In the past, some water quality monitoring and management studies have been carried out for the Ravi River (IPHER 1979, Ali 1979, Ahmed & Tariq 1979). Unfortunately, due to lack of funds, land acquisition issues and other socio- economic factors none of these water quality management plans has yet been implemented. Therefore, the water quality of the River Ravi has continuously been adversely affecting with the increase in wastewater flows with the passage

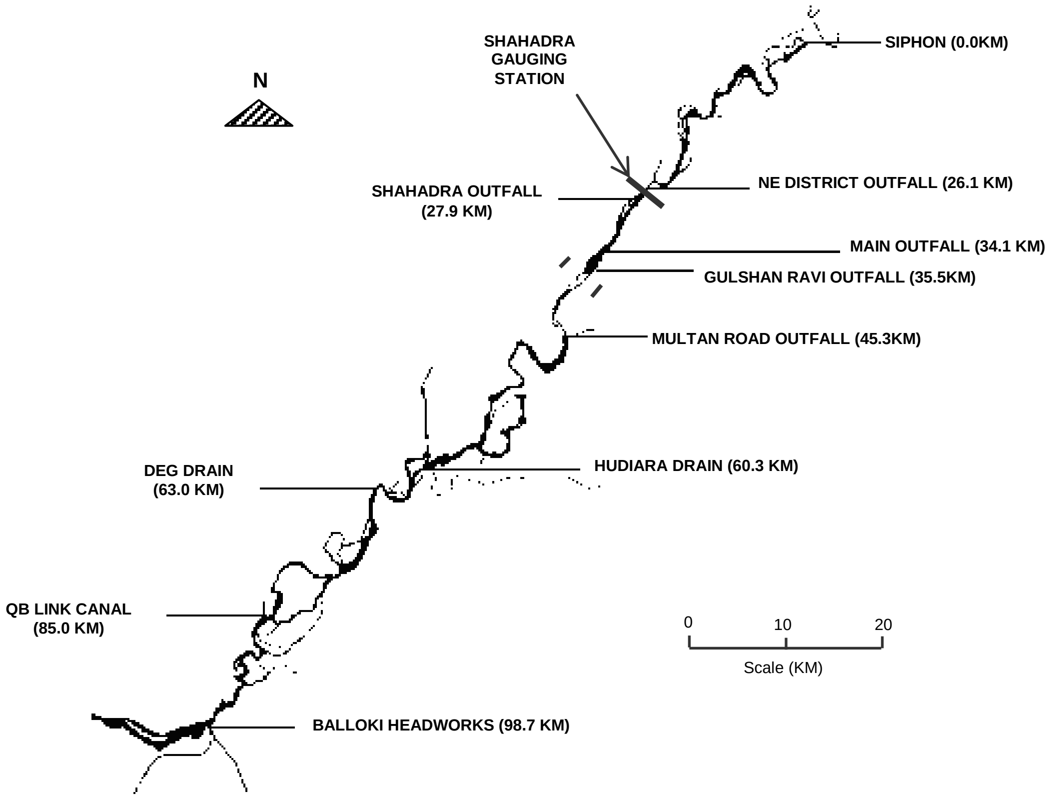

Figure 1: Study reach of the Ravi River showing locations of wastewater outfalls and drains

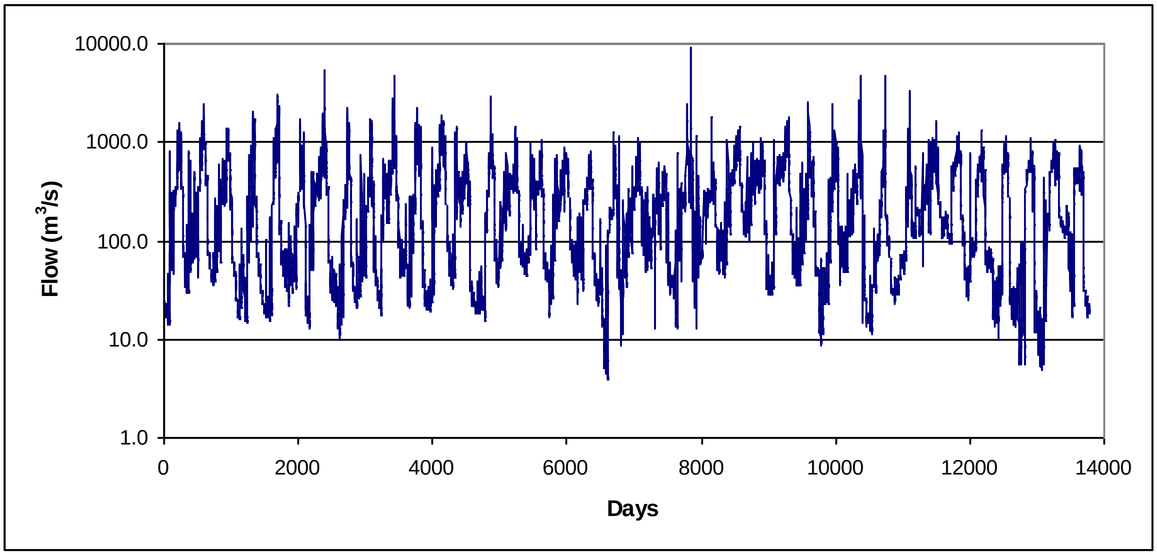

Figure 2: Daily variations in Ravi River flows observed at Shahadra gauging station (Source: Punjab Irrigation & Power Department, 1967-2004 gauge discharge data)

of time due to high population growth and industrialization within and in the proximity of Lahore. The main objective of this paper is to develop a fecal coliform model that can be used for fecal coliform management in the River Ravi to protect its beneficial uses.

2. Methodology

The overall framework used for the FC management of Ravi River is presented in Fig 3. The main components of the approach used in this work are based on river segmentations and the hydrodynamic model coupled with the water quality (i.e., fecal coliform) model. These have been detailed in the following sections.

2.1 River Segmentation and Hydrodynamic Model

The study length of the river is further sub-divided into 9 river segments based on the locations of wastewater outfalls, fresh water tributaries and natural surface drains (Fig 1). Haider & Ali (2010) developed the hydrodynamic model based on the gauge-discharge data observed at Siphon, Shahadra and Balloki gauging stations. The data was collected from Discharge Division of Punjab Irrigation Department (IPD). The hydrodynamic model for the River Ravi was developed in the form of power function to relate mean river velocity to the river flow as (Chapra 1997);

$$U = aQ^b \qquad (1)$$

where Q is the river flow in m^3/s; U is the average velocity of flow in m/s; and a & b are the empirical constants. The power relationships between river velocity and flow along with the estimated values of empirical constants for different reaches are presented in Table 1 (Haider and Ali 2010). As the river flows are extremely variable (Fig 2), two different power equations were developed to cover the flow variations, one for the flows less than $280 m^3/s$ and the other for greater than that (Table 1). Power functions presented in Table 1 are used in this research work to estimate the velocity of water along the river length.

2.2 Water Quality Model

Fecal coliform decay in the rivers is usually modeled as the following first-order kinetics (Chick 1908);

$$\frac{dN}{dt} = -K_b N \qquad (2)$$

where dN/dt is rate of change of FC concentration; K_b is the overall FC die-off rate; and N is the remaining concentration of FC.

For a one-dimensional-multiple reach river under steady-state flow conditions, the hydrodynamic model and the kinetics can be combined to result in the following equation (Chapra 1997, Thomann & Mueller 1987);

$$U\frac{dN}{dx} = -K_b N \qquad (3)$$

The integral form of the equation (3) can be written as;

$$N_x = N_0 e^{-K_b \frac{x}{U}} \qquad (4)$$

where N_x is the concentration of FC at any distance x in the river, N_0 is the initial fecal coliform concentration at the location of wastewater outfall in the river; and x is the distance along the river length.

Table 1: Empirical constants for different river segemnts

Reach No	Reach Description	$U = aQ^b$			
		$Q < 280\ m^3/s$		$Q > 280\ m^3/s$	
		a	*b*	*a*	*b*
1	Siphon to North-East District Outfall	0.01	0.79	18.28	-0.62
2	North-East District to Shahadra Outfall	0.01	0.84	0.05	0.46
3	Shahadra to Main Outfall	0.01	0.84	0.16	0.28
4	Main Outfall – Gulshan Ravi Outfall	0.02	0.78	0.29	0.20
5	Gulshan Ravi to Multan Road Outfall	0.02	0.76	0.07	0.41
6	Multan Road Outfall to Hudiara Drain	0.02	0.73	0.05	0.45
7	Hudiara Drain to Deg Drain	0.01	0.75	0.01	0.69
8	Deg Drain to Qadirabad Balloki Link Canal	0.02	0.61	0.01	0.81
9	QB Link Canal to Balloki Headworks	0.002	0.80	0.001	0.98

Source: Haider & Ali (2010)

The overall fecal coliform die-off rate depends on solar radiations, temperature, salinity, and sedimentation after the discharge of wastewater into the river (Bowie et al. 1985). Therefore, the overall die off rate K_b including these factors can be written as (Thomann & Mueller 1987 and Chapra 1997);

$$K_b = K_{b1} + K_{bi} + K_{bs} \qquad (5)$$

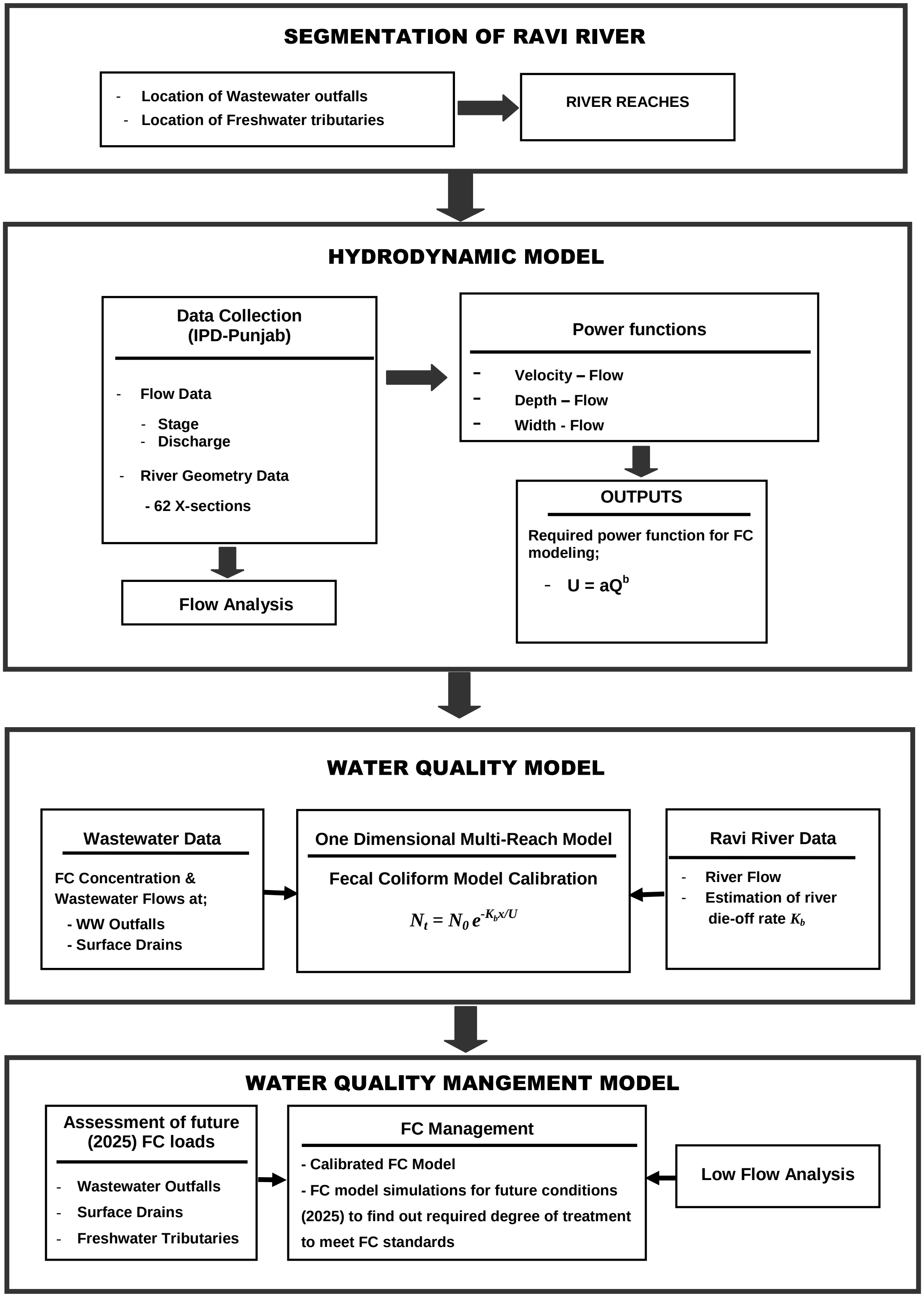

Figure 3: Fecal coliform management framework for the River Ravi

where K_b is the overall decay rate; K_{b1} is the natural mortality rate due to temperature, salinity and predation; K_{bi} is the death rate due to solar radiations; K_{bs} is the net loss of fecal coliforms due to settling and resuspension and K_{ag} is the after-growth rate. The final form of the comprehensive equation including all the factors for overall loss rate can be written as (Thomann & Mueller 1987 and Chapra 1997);

$$K_b = \underbrace{(0.8 + 0.006S)1.07^{T-20}}_{Natural mortality} + \underbrace{\frac{\alpha I_0}{K_e H}\left(1 - e^{-K_e H}\right)}_{Light} + \underbrace{F_p \frac{v_s}{H}}_{Settling} \quad (6)$$

where S is the % sea water; α is a proportionality constant; I_0 surface light energy, cal/cm^2.hr; K_e is an extinction coefficient, m^{-1}; H is the average depth, m; F_p is the fraction of the bacteria that are attached; and v_s is settling velocity of the particle, m/day. These rates have been discussed in detail in Thomann & Mueller 1987 and Chapra 1997. The die-off rate varies with difference in geographical and environmental conditions, because of the variation in above mentioned factors that effects both the growth and death of the micro-organisms (Thomann & Mueller 1987). Kittrel and Furfari (1963) reported a value of 1.3 day^{-1} of K_b (overall TC decay rate) in rivers. For freshwaters a value of 0.8 day^{-1} at 20^{o}C for K_b (TC) is reported by Mancini (1978).

Connolly et al. (1999) used Eq (6) for simulation of FC in Mamala Bay, Hawaii, USA and found that when sufficient data is available to accurately parameterize Eq (6) the equation gives reliable results. However, as these factors change with time, the K_b value determined from this equation for continuous modeling of FC may generate problems (Manache et al. 2007). Elshorbagy and Ormsbee (2006) successfully simulated FC in streams receiving runoff from rural watersheds using a constant K_b value in Eq (4) for the entire simulation period. It is difficult to estimate different components of die-off rate, particularly for large rivers in developing countries, thus, in this study Eq (4) is used with an overall die-off rate *(K_b)* in the River Ravi for FC simulations and management under low flow conditions.

The temperature correction to the overall FC die-off rate can be applied as (Mancini 1978, Thomann & Mueller 1987,);

$$(K_b)_T = (K_b)_{20}(1.07)^{T-20} \quad (7)$$

where $(K_b)_T$ is the decay rate at any temperature, day^{-1}, $(K_b)_{20}$ is the decay rate at 20^{o}C and T is the river temperature, ^{o}C.

3. Results and Discussion

Estimation of River Die-off Rate

To perform fecal coliform modeling four samples were collected in the river through a river survey on 7th July 2009. During the river survey period, the river flow was 431.5m^3/s at the Shahadra gauging station (Fig 1) and average temperature was observed as 24^{o}C. The first sample was collected at upstream of North-East District Outfall (Fig 1) before mixing of wastewater to estimate the background concentration of FC in the River Ravi. The other three samples were collected in between Deg Drain and QB link canal (i.e., the longest reach) to estimate bacterial die off rate coefficient. All four samples were collected with the help of standard river sampler and were prepared for fecal coliform estimation at the site to avoid any change in the reading according to Most Probable Number (MPN) method (APHA 1998). To mark the sampling locations in the river, Global Positioning System (GPS, Magellan Explorist-400) was used. The data observed from the GPS system (i.e, Northing and Easting) were transferred into the drawing tool (AutoCAD Ver 2006) with the help of ProLINK Software.

The river die-off rate is determined by measuring the FC concentration (MPN/100mL) at three points between Deg drain and QB Link canal. The first sample in this reach was collected at 63.4Km, second at 74.8Km and the last one at 88.3Km. Knowing the distance between the survey points the following form of equation (4) was used to calculate the overall die-off rate in the River Ravi;

$$K_b = \frac{\ln\left(\frac{N_0}{N}\right)}{t} \quad (8)$$

where t is the travel time of water segment in the river and was found to be 0.25 days by diving the distance between sampling points to the velocity of flow in this selected river reach. River velocity was calculated by using the hydrodynamic model of the Ravi River (Table 1). K_b is found to be 1.6 day^{-1} at 24^{o}C. The value of K_b at 20^{o}C using equation (7) is 1.2 day^{-1}. These values are consistent with the literature values (Kittrel and Furfari 1963, Mancini 1978 and Mitchell and Chamberlain 1978).

4. Wastewater Flows and Fecal Coliforms

The flows in the River Ravi, Upper Chenab Canal (UCC) and Qadirabad Balloki (QB) Link Canal were collected from IPD-Discharge Division (IPD-Punjab). Wastewater flows data of all the outfalls were collected from WASA-LDA on the same day. The flow in the Deg Drain including Bhed Drain and Choti Deg was collected from Environmental Protection Department – Lahore (EPD 2009). UCC was operational during the river survey period with a flow of 164.2 m^3/s. Deg drain with a flow of 5.7 m^3/s joins the UCC before entering the Ravi River, therefore, combined flow of 169.9 m^3/s was being discharged from the Deg drain into the River Ravi during the survey period (Haider 2010).

The fecal coliforms numbers and the flows at wastewater outfalls and surface drains are given in Table 2. The numbers of fecal coliforms in the river water at 25.3 Km before joining the first wastewater outfall (i.e., NE District Outfall) was found to be 2000 MPN/100mL during the river survey period and is used as background concentration for modeling of fecal coliform in the Ravi River.

Table 2: Fecal Coliform concentration at wastewater outfalls and surface drains

Reach No	Description	Flow (m^3/s)	Fecal Coliforms[a] (MPN/100mL)
1.	North - East District Outfall	9.2	12.5 x 10^6
2.	Shahadra Outfall	2.0	15 x 10^6
3.	Main Outfall	5.7	20 x 10^6
4.	Gulshan Ravi Outfall	3.9	18 x 10^6
5.	Multan Road Outfall	3.0	1 x 10^6
6.	Hudiara Drain	9.85	1 x 10^6
7.	Deg Drain	169.9	2 x 10^6
8.	QB Link Canal	509.2	800

[a] Shah (2009)

5. Calibration of the Fecal Coliform Model

Due to unavailability of present data to calibrate the FC model for the River Ravi model calculations are performed with the monitoring data collected by Institute of Public Health Engineering & Research (IPHER), University of Engineering and Technology, Lahore in year 1978-79. The average wastewater flows and measured FC values at different outfalls, surface drains and freshwater tributaries for the month of December, 1978 are presented in Table 3. Average temperature during the month in the River Ravi was reported as 18^{o}C (IPHER 1978). The average river flow was 53m^3/s during that period and is used for model calibration in this study. Initial fecal coliform concentrations in the River Ravi are calculated assuming complete mixing at the wastewater discharge point using the following mass balance equation (Thomann & Mueller 1987);

$$N_0 = \frac{Q_r N_r + Q_e N_e}{Q_r + Q_e} \tag{9}$$

where N_0 is the FC concentration in the river, Q_r is the river flow upstream of the outfall, N_r is the FC concentration in the river water upstream of the outfall, N_e is the FC concentration in the wastewater, and Q_e is the wastewater flow entering into the river.

The model calibration was carried out using the wastewater inputs given in Table 3 and the K_b estimated form the river data as mentioned earlier. The temperature correction to the K_b was applied using equation (7). The calculated FC values using the equation (4) and the measured values are presented in Figure 6. The results shown in Figure 4 presents reasonable agreement between the simulation results with the FC levels in the river. These calibration results also reveal that the overall FC die-off rate estimated under medium flow conditions (i.e., river flow > 280m^3/s) can be effectively utilized for low flow conditions, as the river flow during calibration is 53m^3/s. Thus the calibrated FC model can be utilized for FC management purposes.

Table 3: Wastewater data used for Ravi River Fecal Coliform model calibration

Sr No	Wastewater Outfalls/ Surface Drains B	Flow (m^3/s)	Fecal Coliform Concentration (MPN/100mL)
1.	NE District Outfall	0.92	1 x 10^6
2.	Main Outfall	0.80	1.1 x 10^6
3.	Multan Road Outfall	1.34	1.2 x 10^6
4.	Hudiara Drain	3.38	1 x 10^6
5.	Deg Drain	130.4	800
6.	QB Link Canal	400	800

Source: (IPHER 1978)

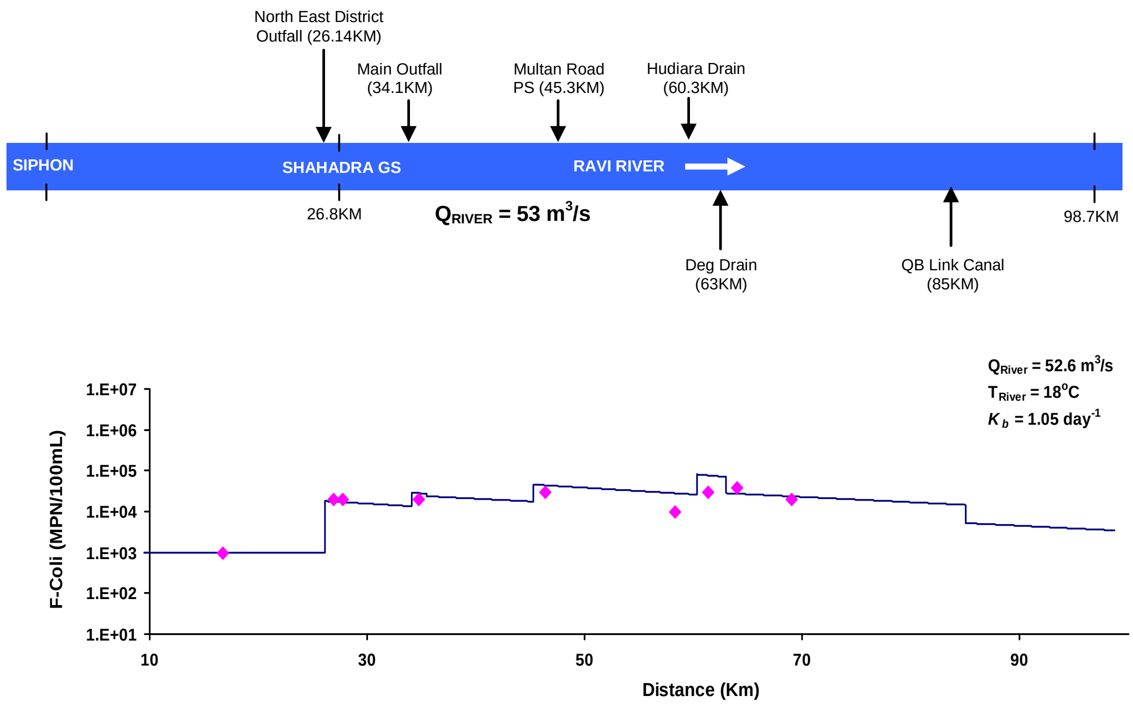

Figure 4: Simulation results for the calibration of fecal coliform model based on IPHER 1978 data

6. Fecal Coliform Management

Different regulatory agencies have established FC standards for different beneficial uses (Table 4). Due to discharge of untreated wastewaters into the Ravi River, the river is fecally polluted particularly under low flow conditions. Recreation and agriculture are the most important beneficial uses of the Ravi River with standards less than 1,000MPN/100mL (WHO 1989 and Government of District Columbia 1981). The fecal coliforms in Ravi River at Balloki after receiving high dilution of freshwater from QB Link canal was found to be 12,000 MPN/100mL during the survey period, even when the flow in the river was 431.5 m^3/s. Thus, there is a need of FC management by using a calibrated FC model.

Table 4: Fecal Coliform standards for different beneficial uses

Sr No	Beneficial Use	Fecal Coliform Standards (MPN/100mL)
1.	Public water supply [a]	0
2.	Agriculture [a]	1000
3.	Contact recreation [b]	100 – 1000
4.	Fishing [c]	100 – 1000

[a] WHO 1989; [b] Government of District Columbia 1981; [c] City of New York 1979

Water quality controls usually are determined for critical low flow conditions. Haider (2010) estimated the minimum river flow to be 9.2 m^3/s (325 cfs) by probability analyses of 37 years flow record (IPD-Punjab 1967-2004).

The calibrated FC model has been used to calculate the FC levels in the river using the present pollution loads (Table 2) under low flow conditions. The results are shown in Figure 5a. These results show that the River Ravi needs an urgent implementation of a water quality management strategy. Water quality management strategies including wastewater treatment facilities are commonly developed for 15 years design period (McGhee 1991). Haider (2010) estimated the future wastewater flows for FC management of the River Ravi. The wastewater flows and loading for year 2025 are estimated and it is found that total wastewater flow from all the outfalls and surface drains will be about 56m^3/s. It means that the future wastewater flow will be about 6 times higher than the present river flow (Haider 2010).

Reduction in FC levels in wastewater can be achieved through various treatment levels. Secondary treatment with disinfection can results in up to 6 log reduction. The calculated FC concentrations in raw wastewater and after applying different log reductions to wastewater and surface waters for the year 2025 are presented in Table 5. The results of the model simulation after applying secondary level wastewater treatment with disinfection at the outfalls and surface drains are shown in Figure 5b. These results suggest that, 6 log FC reduction is required at the wastewater outfalls, whereas, 5 log reduction would be sufficient for the surface drains (i.e., Hudiara and Deg drains) to meet desirable agriculture standards in the River Ravi. These high levels of FC reduction can be achieved with secondary treatment through aerated lagoons, trickling filters or activated sludge process followed by disinfection using chlorine or ultraviolet radiations (Metcalf & Eddy 1979 and Thomann & Mueller 1987).

Table 5: FC flows and concentration at wastewater outfalls and surface drains in year 2025

Reach No	Description	Flow (m^3/s)	Fecal Coliforms [a] (MPN/100mL)	log Reduction	FC after reduction (MPN/100mL)
1.	North - East District Outfall	11.3	12.5×10^6	6	1,250
2.	Shahadra Outfall	2.3	15×10^6	6	1,500
3.	Main Outfall	6.7	20×10^6	6	2,000
4.	Gulshan Ravi Outfall	5.5	18×10^6	6	1,800
5.	Multan Road Outfall	3.5	15×10^6	6	10,000
6.	Hudiara Drain	17.5	1×10^6	5	1500
7.	Deg Drain	9.3	2×10^6	5	2,000
8.	QB Link Canal	509.2	800	-	-

[a] Shah (2009)

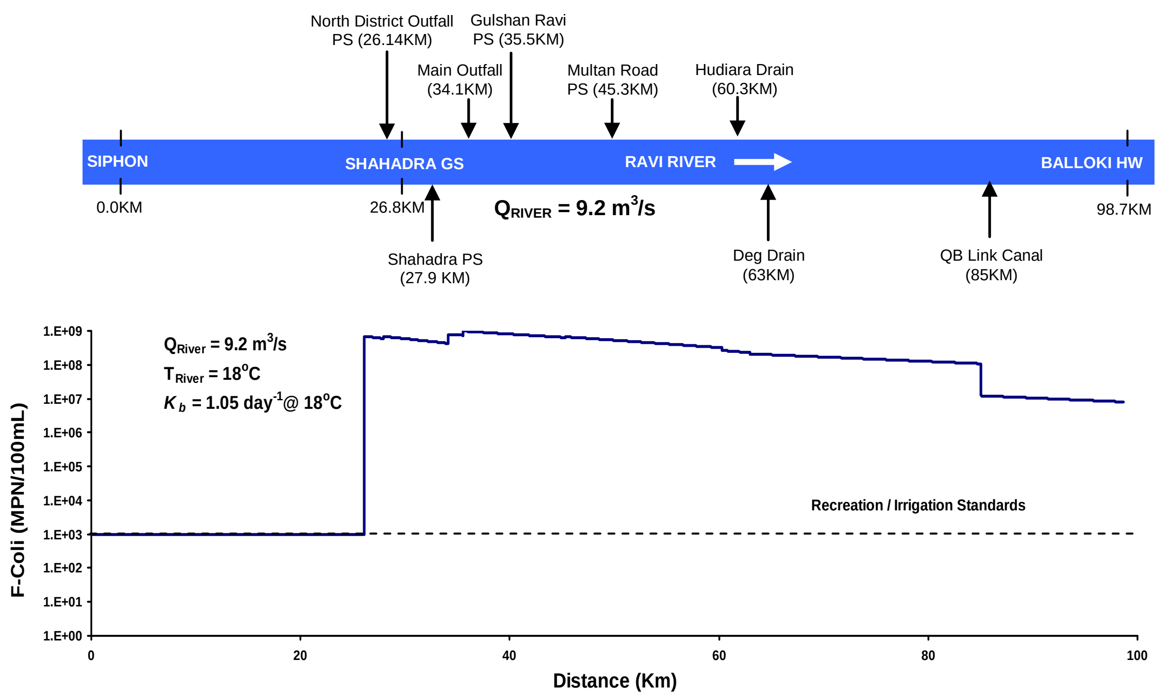

Figure 5a: FC Simulation results for present pollution loads at minimum river flow

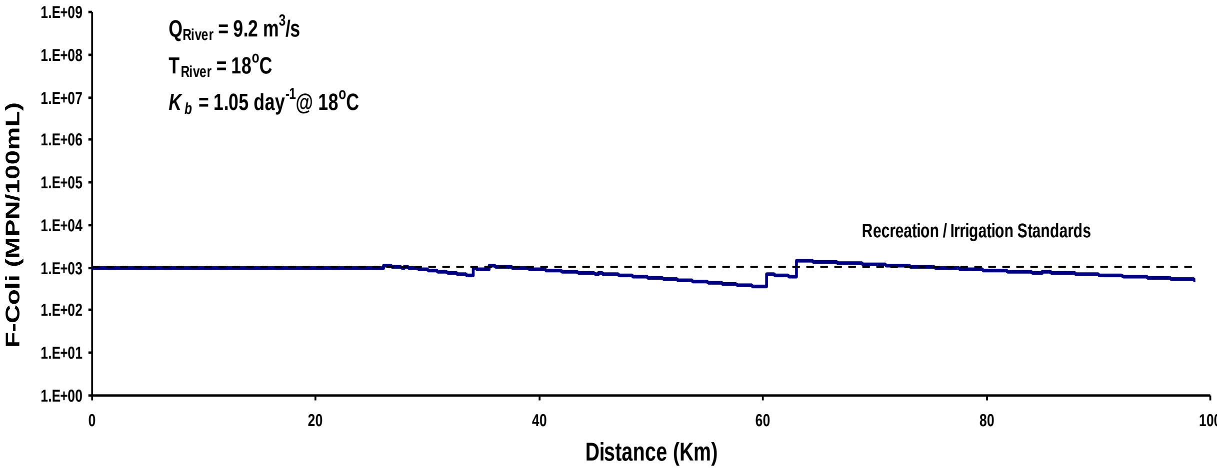

Figure 5b: FC Simulation results for future pollution loads in year 2025 at minimum river flow with secondary treatment plus disinfection.

7. Conclusions

The overall fecal coliform decay rate *(K_b)* estimated (following first order kinetics) through river survey under medium flow conditions > 280m^3/s) was found to be 1.2 day^{-1} at 20^{o}C which is consistent with the reported values in literature. The FC model calibration was done under low flow conditions (i.e., < 280m^3/s) and the field values show reasonable agreement with the model results. These results show that overall FC die-off rate determined can be effectively used for FC modeling and management in large rivers with highly variable flows in developing countries when resources are limited.

The FC die-off rate estimated during medium flow conditions (i.e., 431.5m^3/s) in this study is used for calibration of the model for past low flow conditions (i.e., 52.6m^3/s). The calibration results without adjusting the estimated die-off rate show the robustness of the river hydrodynamic model (consisting of different power functions to deal with large flow variations) for FC management under variable flow conditions.

The fecal coliform model results reveal that river water is fecally contaminated even under higher flow conditions and is not complying with agriculture standards of 1000 MPN/100mL. FC simulation results for low flow future conditions reveals that FC reductions up to 6 log and 5 log are required at the wastewater outfalls and surface drains respectively.

8. Acknowledgements

The research work presented in this paper is funded by the University of Engineering and Technology (UET), Lahore. The support of laboratory staff during the sampling and experimentation is also acknowledged.

References

[1] Ahmed K. and Tariq N.M., “Ravi-River A Biological Survey”, Institute of Public Health Engineering & Research, Report No. 042-06-79, Univ. of Engg., & Tech., 1979, Lahore.

[2] Ali R.M., “A field study of fecal streptococci in the River Ravi”, Institute of Public Health Engineering & Research, Report No. 041-06-79, Univ. of Engg., & Tech., 1979, Lahore.

[3] APHA, “Standard Methods for the Examination of Water and Wastewater”, 20th Edition, American Public Health Association, 1998, Washington, DC20005-2605.

[4] Bowie, et.al., “Rates, constants, and kinetics formulation in surface water quality modeling”, 2nd Editions, USEPA/600/3-85/040, 1985, Athens, GA.

[5] Chapra S.C., “Surface water quality modeling”, McGraw Hill International, Civil Engineering Series, 1997, Singapore.

[6] Chick, H., "An investigation of the laws of disinfection", J. Hyg. (Lond), 8(1), 92–158, 1908.

[7] City of New York, "Areawide water treatment management planning program", Section 208, NYC Dept. of Env. Prot., 8 Chapters, 1979.

[8] Connolly et.al., "Modeling fate of pathogenic organisms in coastal waters of Oahu", Hawaii, Journal of Environmental Engineering, 125(5), 398–406, 1999.

[9] Elshorbagy, A., and Ormsbee, L., "Object-oriented modeling approach to surface water quality management", Environ. Modell. Software, 21, 689–698, 2006.

[10] EPD – Punjab, "Installation of Wastewater Treatment Plants to save River Ravi from Pollution", District Sheikhupura, Environmental Protection Department, 2009, Lahore.

[11] Government of the District of Columbia, "Water quality standards for interstate waters of the District of Columbia", Department of Env. Serv, Env. Health Admin., Bureau of Air and Water Quality, Water Hygiene Division, 16 pp., 1981.

[12] Haider H., "Water Quality Management Model for Ravi River", PhD Thesis, Institute of Environmental Engineering and Research, UET, 2010, Lahore.

[13] Haider H, Ali W., "Development of Dissolved Oxygen Model for a Highly Variable Flow River: A Case Study of Ravi River in Pakistan", Environmental Modeling and Assessment Journal, 15 (6): 583-599, 2010a.

[14] IPHER, "Ravi River Pollution Study-III", IPHER, Report No. 040-03-79, Univ. of Engg., & Tech., 1979, Lahore.

[15] Kittrell B.A., and Furfari S.A., "Observation of coliform bacteria in streams", Journal of Water Pollution Control Federation, 35, 1361-1385, 1963.

[16] Manache G., Meching C.S., and Lanyon R., "Calibration of a Continuous Simulation Fecal Coliform Model Based on Historical Data Analysis", Journal of Environmental Engineering, 133(7), 681-691, 2007.

[17] Mancini J. L., "Numerical estimates of coliform mortality rates under various conditions." Journal of Water Pollution Control Federation, 50(11), 2477–2484, 1978.

[18] Shah M., "Fecal Coliform Modeling of Ravi River", MSc Thesis, IEER, UET, 2009, Lahore.

[19] Thomann V. R and Mueller A.J, "Principles of Surface Water Quality Modeling", Harper International Edition, Harper & Row, 1987, New York.

[20] WHO, "Health Guidelines for the use of wastewater in agriculture and aquaculture", Geneva, WHO Technical Report Series, No. 778, 1989.