USE OF WATER QUALITY MODELS IN MANAGEMENT OF RIVER WATER QUALITY

by

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Abstract

With increasing urban and rural development, the quality of rivers is affected more and more adversely and often these very same rivers are sources of water supply. Therefore the need to monitor these rivers systematically to maintain the quality within acceptable limits has become extremely vital. This study deals with the development of a water quality model for river systems to predict how the system will perform, given the quantities and quality of waste effluent inflows and tributary inflows in to the river system. The study includes the development of a computer programme for the model. The article highlights the need to have a regular sampling programme and a quality monitoring system for local rivers. It also proposes what activities such a programme should consist of. (Ref. 8)

1.0 Introduction

With increasing urban and rural development the quality of rivers deteriorates increasingly due to increasing quantities of used water discharged into our rivers.

In Sri Lanka the urban population mostly depend on river water for their domestic needs. For example, Greater Colombo, Kandy, Galle, Matara, Negombo and several other cities depend solely on rivers for drinking water supplies. Hence it is mostly vital to maintain good quality water in the major rivers supplying the drinking needs.

Therefore, we must manage our rivers systematically to maintain water quality within acceptable limits. Also with the application of computers which are widely used in many fields, the necessary computations would be extremely easy.

This article deals with the use of mathematical models in managing river water quality and the development of a steady state river water quality model and a computer programme.

The limitations in application of such a model to local river systems due to the inadequacy of data must be stressed. However, it is felt, that this study would create an awareness of this problem and help to improve the situation. (Ref. 8)

2.0 How Mathematical Models can be used

When discussing about inflows of used water into streams and rivers, they may be divided into two categories, viz: 1) point source discharges of treated waste water, ie. from municipalities and industries, and 2) non-point source flows or diffused flows, ie. from irrigated agriculture, urban water run-off, etc.

The discharge of used water will affect the river water quality through the direct effect of mixing of the two waters of different qualities and through the processes taking place in the mixed stream. The inflows of used water have to be managed if the quality of water along the river is to be maintained within acceptable limits stipulated by the authorities.

For formulating and solving such river pollution problems mathematical modelling has been used for several decades in many developed countries.

In management of stream water quality both stream standards and effluent standards are used; they are complementary. For example if the effluent standards

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are not adequate to achieve the stream standards more stringent effluent standards could be adopted. Whether or not a given effluent standard will result in the achievement of a given stream standard can also be investigated through the use of such a water quality model.

On the other hand, it may be possible to relax the effluent standards in certain stretches of a stream within limits by carefully studying how the given effluent loads affect the quality of the stream, if the resulting water quality is far above the standards. In this area too a water quality model would be of great use.

The main uses of such a model once developed would be,

1. to set standards for effluents from industries and municipal treatment works, and
2. to evaluate and decide alternatives to meet water quality objectives.

Another very important use is the determination of sensitivity of the model outputs to the input quality parameters used in the model, from which it will be possible to determine the degree of accuracy required in assessing these parameters.

One must understand that the development and use of such a model essentially requires the availability of the necessary data, viz, the water quality data as well as the river basin hydrological data, and the physical characteristics of the river. In the absence of this data, to the required extent, it is always necessary to make certain approximations and assumptions. (Ref. 8)

3.0 Objectives of the Water Quality Model

The specific objectives of the model would be,

1. to forecast the river water quality, given the quantity and quality of a set of effluent discharges.
2. to calculate the safe load for discharges along the river for the given water quality standards.
3. determination of the applicable critical minimal stream flow.
4. to find the assimilative capacity of the river for other waste water discharge.
5. determination of revision, when appropriate, of standards for quality of receiving rivers or streams and the waste effluent discharges.

4.0 Steady State Water Quality Model

4.1 The Structure

For the modelling purpose, a stretch of a river is considered and this is divided into n reaches with n+1 nodal points. The reach between two consecutive nodal points i and i+1 is considered as the reach i. Activities associated with each reach are assumed to occur at the beginning and at the end of the reach (Fig. 1).

These activities include one or more of the following :

Outflows
- Extraction for water supply etc.
- Flow losses along the reach due to evaporation and percolation.

Inflows
- Effluent discharges from waste treatment plants
- Run offs, and seepage along the reach
- Tributary inflows

4.2 Parameters

Only bio-degradable and thermal wastes are considered in the model. The parameters used are mainly of five categories. (Ref. 8)

1. Hydrologic Parameters (Ref.1 pg.17-18)
2. Hydraulic Parameters
3. Biochemical oxygen demand (oxygen uptake)
4. Dissolved oxygen (oxygen sources)
5. Temperature

Some hydraulic parameters related to detention time in each reach are used as supporting input data. The river cross section is assumed to be trapezoidal and the average values of side slopes and bed width for each reach are used as data. The rating curves for each river stretch are also required. These give the relationship between the discharge (Q) and the depth (d), for each stretch. Assuming a linear relationship in the range of low flows, this curve would take the form

$$d = mQ$$

where m is the slope of the rating curve. Values of m are used as input data. (Ref. 8)

Hydrologic parameters -

1. Flows and temperatures in the river at the n+1 points
2. Equilibrium air temperature
3. Length of the river stretches

Values of BOD, DO and temperature of the following are required.

- the river at each of the n+1 nodal points
- waste effluent inflows into the river at these n+1 nodal points
- tributary inflows at these n+1 points

In addition, BOD rate constant (ref. 7-pg.645) and reaeration rate constant (ref.7-pg.653) at equilibrium air temperature 20°C, and the thermal decay rate constant (ref. 5-pg.234 and ref.2-pg.255) for each reach have been used as inputs.

4.3 Assumptions

The following assumptions were made in the construction of the model. (Ref. 8).

1. Steady state of flow in the river
2. The cross section is trapezoidal and constant along each of the specified reaches.
3. Other physical characteristics such as depth and slope are constant along each reach.
4. Longitudinal dispersion is neglible
5. All concentrations are uniform over the cross section of the river
6. Chloride concentration is negligible. No tidal effects or saline water intrusions are present
7. Tributary inflows and waste effluent inflows along each reach will take place at the starting point of the reach
8. Outflows from the river along each reach would be at the end of the reach.
9. There is an immediate perfect mixing around every discharge and tributary inflow.
10. All rate constants and equilibrium air temperature along each reach are constant.

It was further assumed that the following processes contributing to BOD and oxygen variation are not present.

i. The removal of BOD by sedimentation.
ii. The addition of BOD along the stretch by the scour of bottom deposits or by the diffusion of partly decomposed organic products from the benthal layer to the water above.
iii. The removal of oxygen from the water by diffusion into the benthal layer to satisfy the oxygen demand in the aerobic zone of this layer.
iv. The addition of oxygen by photosynthetic action of plankton and fixed plants.
v. The removal of oxygen by the respiration of plankton and attached plants.

4.4 Formulation of the model

This consists of two main parts -

1. A set of mass balances which are applied to each tributary and effluent discharging to the river system and to each outflow or extraction from the river.
2. A set of equations which represent the variation in concentration taking place along the river between discharges.

4.5 Processes within the System

4.5.1 Oxygen uptake (deoxygenation) and Reaeration

When a high BOD effluent is discharged into a river, the oxygen in the water is used up for the biological oxidation and a reduction in D.O. (dissolved O_2) takes place.

Since we are dealing with somewhat high BOD loads it can be assumed that the oxygen uptake in this process is adequately described by the first order kinetics given below :-

$$\frac{dl}{dt} = K_1 L \qquad (1) \text{ (Ref. 2)}$$

K_1 = BOD rate constant (time^{-1}) at equilibrium air temperature. By integrating between t = 0 and t

$$L_t = L_o e^{-Kt} \qquad (2)$$

Where L_o = Ultimate BOD, ie. BOD_u remaining to be exerted at time O, or just after mixing.

L_t = BOD remaining not be exerted at time t.

The equation for the dissolved - oxygen deficit or D.O. deficit of river can be obtained from the model for D.O. viz;

Streeter - Phelps equ^n (Ref. 2)

$$\frac{dc}{dt} = -K_1 L_t + K_2 (C_s - C) \qquad (3)$$

where C = D.O. concentration
C_s = Saturation DO concentration
K_2 = Reaeration rate constant at equilibrium temperature.

In terms of deficit

$$C_s - C = D$$

$$\frac{dD}{dt} = \frac{-dC}{dt}$$

Then equation (3) is given as

$$\frac{dD}{dt} = K_1L_t - K_2D \qquad (4)$$

By integrating from t = 0 to t and substituting

$$D_t = \frac{K_1Lo}{K_2-K_1}(e^{-K_1t} - e^{-K_2t}) + D_oe^{-K_2t} \qquad (5)$$

Where, D_t = D.O. deficit at time t
D_o = initial D.O. deficit

4.5.2 The Temperature Response

When thermal effluents are discharged and there is a rise in temperature immediately after the mass balance, the gradual decrease in temperature within the stretch is described by the following differential equation :- (Ref. 2 & 5)

$$\frac{d(T_t - T_e)}{dt} = K_3(T_t - T_e) \qquad (6)$$

By integrating,

$$T_t = (T_o - T_e)e^{-K_3t} + T_e \qquad (7)$$

Where, t = time in days
T_t = water temperature in °C at time t
T_o = water temperature in °C at time t = o
T_e = equilibrium air temperature of the river basin, °C
K_s = Thermal Decay Rate constant days^{-1}

4.6 The Model

Using these equations, relationships are derived for the quality parameters at the starting point of the reach immediately after mixing and at the end point after the processes along the given reach.

Figure 1 and Tables 1, 2a and 2b show the discharges and quality parameters in the river, waste effluent inflows, tributary inflows and outflows in reach i as used in these equations.

For each reach values of m_i, B_i, C_i, d_i and l_i are given as input data.

Applying mass balance equations at the point of discharge of waste effluents and tributaries at upper end of reach i, the discharge immediately after mass balance will be,

$$Q_i = Q_{i-1} - g_i + p_i + q_i$$

The DO deficit, BOD and temperature of the water immediately after complete mixing will be as follows :-

$$D_i' = \frac{D_{i-1}''(Q_{i-1} - g_i) + j_ip_i + r_iq_i}{Q_i}$$

$$B_i' = \frac{B_{i-1}''(Q_{i-1} - g_i) + u_ip_i + w_iq_i}{Q_i}$$

$$T_i' = \frac{T_{i-1}''(Q_{i-1} - g_i) + \tau_{wi}p_i + \tau_{ti}q_i}{Q_i}$$

The DO deficit of waste effluent inflows and tributaries used in the above equations are determined by the following equations :-

$$j_i = a_{si} - a_i$$
$$r_i = b_{si} - b_i$$

The saturation DO concentration a_{si} and b_{si} are found from the array of values given.

Applying temperature response equation, the temperature at lower end of the reach will be

$$T_i'' = (T_i' - T_{ei})e^{-K_it_i} + T_{ei}$$

BOD and reaeration rate constants at equilibrium air temperature are given by,

$$K_{ei} = K_i\theta_b^{T_{ei} - 20}$$

$$K_{ei}' = K_i'\theta_r^{T_{ei} - 20}$$

Average values for BOD and reaeration rate constants for reach i will be,

$$K_i^{'''} = K_{ei}\left\{\frac{\theta_b^{(T_i^{'} - T_{ei})} + \theta_b^{(T_i^{''} - T_{ei})e^{-K_i^{''}t_i}}}{2}\right\}$$

$$K_i^{''''} = K_{ei}^{'}\left\{\frac{\theta_r^{(T_i^{'} - T_{ei})} + \theta_r^{(T_i^{''} - T_{ei})e^{-K_i^{''}t_i}}}{2}\right\}$$

DO deficit and BOD at lower end of reach i will be,

$$D_i^{''} = \frac{K_i^{'''}B_i^{'}}{K_i^{''''} - K_i^{'''}}\left(e^{-K_i^{'''}t_i} - e^{-K_i^{''''}t_i}\right) + D_i^{'}e^{-K_i^{''''}t_i}$$

$$B_i^{''} = B_i^{'}e^{-K_i^{'''}t_i}$$

DO concentration values at upper and lower ends of reach i are

$$C_i = C_{si} - D_i$$
$$C_i = C_{si} - D_i$$

C_{si} and C_{si} are found from the array of values for the given temperatures.

t_i, the time taken to travel along the reach can be represented in terms of known parameters as follows :

$$t_i = 10^3\left\{B_i l_i m_i + \frac{m_i^2 Q_i l_i}{2}(c_i + d_i)\right\}$$

4.7 Computer Programme

Using this mathematical formulation in paragraph 4.6 a computer programme was written in the Fortran language.

5.0 Application

This model was applied to the stretch of Kelani Ganga from Hanwella to the estuary. Most of the input data were assumed since these were not available. Calibration (ref. 3 - pg. 366) of the model could not be carried out due to the insufficiency of actual data for comparison with the values forecast by the model. With a proper sampling programme and sufficient data made available, tuning (ref. 3 pg. 229) of the rate constants can be done.

The sensitivity analysis (ref. 3 pg. 366) was carried out by varying the calculated parameters used as input data within a certain range. The confidence limits for the determinands is taken as 95%.

It was observed that an inaccuracy of even 15% in measuring the temperature of waste effluent inflow and tributary inflow and 30% inaccuracy in the thermal decay rate constant may be allowed since the results would be still within the confidence limits.

However, the BOD and reaeration rate constants, DO concentration and BOD have to be assessed rather accurately, since even with 5% or 10% changes in these parameters resulting determinands were less than the 95% confidence limits in some reaches. This is specially so, as all these parameters are all interconnected in the processes taking place within the river system. The effect of inaccuracy of one of these parameters at any time may be analyzed by carrying out the calibration with such changes in the input parameters.

6.0 Proposals

A regular sampling programme and a quality monitoring system is proposed for the local rivers, comprising the following :

6.1 Hydraulic Data in Rivers

Gauge stations for obtaining the hydraulic data are recommended to be set up at key points and at suitable intervals along the river. Measurements of flow and velocity should be taken at suitable frequent intervals, specially at low flows. The river cross sectional details at these stations and at various other sections and also the details required for the rating curves should be measured regularly.

6.2 Quality Data in Rivers

Quality monitoring stations should be selected to encompass all pertinent stretches; above and below all waste water discharges and tributary inflows.

Sampling data to be collected are BOD, DO and temperature. The frequency of sampling should be increased during periods of low and high temperature.

6.3 Tributaries

Similar sampling should be done in the tributaries at the points of discharge to the river system.

6.4 Waste Effluent Discharges

Routine measurement of quantities and quality should be done in waste effluent discharges. (Frequency to be increased during periods of low flow and high temperature). Quality parameters to be measured are BOD, DO and temperature.

7.0 Conclusion

From the foregoing it is seen that it is not possible to control the quality of river water without establishing a regular quality monitoring system and that the use of a computer model essentially requires the availability of hydraulic, hydrologic and quality data. In the absence of such data it is necessary to make approximations and assumptions which would invariably impair the effectiveness in application of the model.

With an adequate sampling programme as proposed, initially at least for the rivers which face risk of pollution, the quality of these rivers can be monitored and controlled using this model or any other similar model.

8.0 References

1. Rinaldi, S. Modelling and Control of River Quality McGraw-Hill, New York, 1972.
   (Chap. 17, River Water Quality Model Construction)
   (Chap. 18, Basic Approach to Water Quality Modelling)
   (Chap, 19, Application of Water Quality Models)
2. Brebbia, C.A. (Edited by), Proceedings of the International Conference held at the University of Southampton, Sept. 8-12, 1975. Pentech Press, London 1975.
   (Chap. on A Water Quality Optimization Model for nonserial river systems)
3. Stiff, M.J. (Edited by), River Pollution Control, Ellis Horwood Ltd., Chichester, 1980.
   (Chap. 15, The Interaction between Data Collection and Water Quality Modelling)
   (Chap. 22, The systems analytical approach)
   (Chap. 24, The River Ouse Mathematical Model)
4. Exkenfelder, W. Wesley, Principles of Water Quality Management, CBI Publishing Company, Boston, 1980.
5. Biswas, A.K., Systems Approach to Water Management, McGraw-Hill, New York, 1976.
6. Mara, Duncan, Sewage Treatment in Hot Climates, John Wiley Sons, Chichester, 1978.
7. Fair G.M., Geyer J.C., Okun D.A., Elements of Water Supply and Waste Water Disposal, John Wiley & Sons Inc. U.S.A. 1971.
8. Karunaratne, Geethi, A Steady State Water Quality Model for River Systems, M.Eng., Dissertation, University of Moratuwa, 1984.

q_i – Total tributary inflows

p_i – Total waste effluent inflows

g_i – Total out flows

Qi-1, Qi, Qi+1 –
Flows in the river in reaches i-1, i and i+1 respectively.

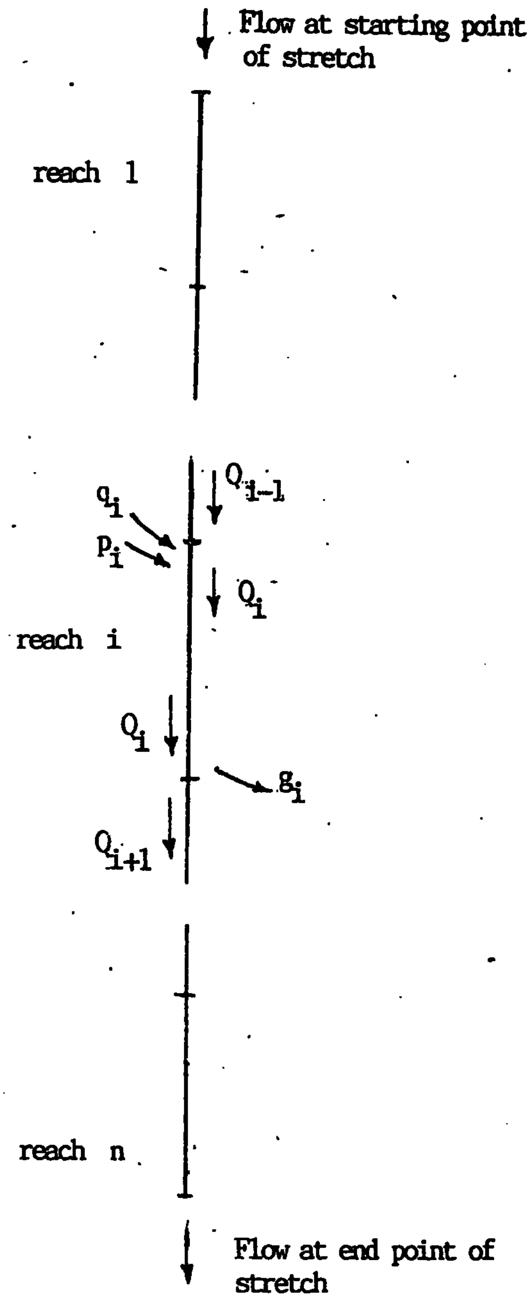

Fig. 1 – SCHEMETIC DIAGRAM OF THE RIVER SYSTEM

TABLE 1

DISCHARGES AND QUALITY PARAMETERS FOR MATHEMATICAL FORMULATIONS

Parameter	In river			In waste effluent inflows at upper end of reach I	In tributary inflows at upper end of reach i	In outflows at lower end of reach i
	Before entering reach i	at upper end of reach i	at lower end of reach i			
Discharge, 1/d	Q_{i-1}	Q_i	Q_i	p_i	q_i	g_i
DO concentration, mg/1	C''_{i-1}	C'_i	C''_i	a_i	b_i	similar to that in river at lower end of reach i
SDO concentration, mg/1	$C''_{s\ i-1}$	C'_{si}	C''_{si}	a_{si}	b_{si}	- do -
DO deficit, mg/1	D''_{i-1}	D'_i	D''_i	j_i	r_i	- do -
Ultimate BOD, mg/1	B''_{i-1}	B'_i	B''_i	U_i	W_i	- do -
Temperature, °C	T''_{i-1}	T'_i	T''_i	wi	ti	

TABLE 2a

HYDRAULIC AND PHYSICAL PARAMETERS

Parameter	Notation for reach i
BOD rate constant at 20°C, $days^{-1}$	K_i
-do- at equilibrium air temperature, days	K_{ei}
-do- at average water temperature in reach i, $days^{-1}$	K_i'''
Reaeration rate constant at 20°C, $days^{-1}$	K_i'
Reaeration rate constant at equilibrium air temperature, days	K_{ei}'
Reaeration rate constant at average water temperature in reach i, $days^{-1}$	K_i''''
Thermal decay rate constant, $days^{-1}$	K_i''
Equilibrium air temperature, °C	T_{ei}
Temperature activity constant for BOD rate constant, K_i	b
Temperature activity constant for reaeration rate constant, K_i'	r

TABLE 2b

RATE CONSTANTS

Parameter	Notation for reach i
Length of reach, m	l_i
For trapezoidal section, Average bedwidth, m	B_i
Average side slope, left	C_i
Average side slope, right	d_i
Average depth	D_i
Average cross sectional area, m^2 Average velocity, m/s	A_i V_i
Time taken to travel along the reach, days	t_i
Average slope of rating curve, m/(1/d)	m_i