Journal of Water Sustainability, Volume 3, Issue 1, March 2013, 29–43

Dispersion Prediction in the Uppanar River of South East Coast of India

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ABSTRACT

This paper presents the estimation of dispersion coefficient in a small segment of a natural river. The dispersion coefficient is a fundamental parameter in hydraulic modelling of river pollution and important to evaluate the characteristics of pollutants behaviour in a natural river. Based on the measured data of dissolved oxygen (DO), nitrate-nitrogen and reactive silica, the dispersion coefficient was determined along the three sampling stations I, II and III in the Uppanar River (11° 42' 34"N 79° 46' 88"E), Cuddalore district, Tamil Nadu, India. The calculated values of dispersion number (D/uL) along station I, station II and station III obtained for DO were 0.122, 0.136 and 0.152, for nitrate-nitrogen, 0.142, 0.136, and 0.163 and for reactive silica 0.114, 0.129 and 0.116, respectively. It was pragmatic that all the three sampling stations were having dispersion numbers less than 0.2. The experimental data obtained were modelled by adopting a dispersion model. The statistical quality of the dispersion modelling was high (R^2 = 0.9992, 1.0 and 0.9983 for stations I, II and III respectively, between experimental and theoretical DO values). Furthermore, it was also observed that there was a one to one correlation among the theoretical and observed values. The results could show the superiority of the proposed model.

Keywords: Dispersion model; dispersion number; Uppanar River

1. INTRODUCTION

Water quantity and quality are an integral part of the natural hydrologic environment. The quality of a river is influenced by human activities such as the discharge of industrial, domestic effluents, the use of agricultural chemicals and lands (Ho et al., 2002; Refsgaard et al., 2007). Moreover, the unsustainable exploitation of the river water beyond its carrying capacity has resulted in decline of quality. The assessment of water quality in developing countries has become a critical issue in recent years due to the concern that fresh water will be a scarce resource in the future. Therefore, proper assessment, development and management of water resources require full understanding of the environmental processes and their interactions (Ng, 2006).

Rivers represent a major way for the transportation of dissolved and particulate pollutants from continental to coastal regions, as well as to the oceans. During the transportation process, several factors (e.g., physical, chemical and biological) can modify the original geochemical forms and source signatures (Souza et al., 2010). When harmful pollutants enter a river system, it may have a critical impact to the ecology of the river and humans. In the early stages of the transport process after the pollutant are discharged into the river, advection plays an important role in the trans-

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DOI: 10.11912/jws.2013.3.1.29-43

portation of pollutants. In the later stages, when the cross sectional mixing is complete, the process of longitudinal dispersion becomes important (Ahsan, 2008; Fogler, 1986; Jobson, 1997; Seo and Cheong, 1998). The dispersion coefficient represents the rate of pollution and it is the most desired parameter in any air or water quality modelling study (Shu et al., 2009; Toprak and Savci, 2007).

Water quality modelling is used to predict contaminant transport and distribution in rivers, estuaries and coastal zones. In fact, the use of mathematical models to address environmental and ecological problems is increasing, evidencing their role as a scientific tool, to improve understanding of ecosystem properties (Azevedo et al., 2010). Till now little attention has been given to water pollution modelling and no attempt is made using the dispersion modelling especially, in the Uppanar River. In this study, based on the measured data of dissolved oxygen (DO), nitrate-nitrogen and reactive silica, the model parameter - dispersion number was determined experimentally and theoretically to investigate the characteristics of pollutants transport in the Uppanar River.

2. METHODOLOGY

2.1 Study area

The Uppanar River (11°42’34”N 79°46’88”E), is situated in Cuddalore district of Tamil Nadu State in south-east India (Figure 1). The river runs in parallel to the coast south of Cuddalore town to a distance of about 20 km and confluences with the Bay of Bengal through a mouth of Gadilam River. The tidal influence extends to about 15 km from the mouth of the river (Ayyamperumal et al., 2006). On the bank of the river towards inland with close proximity to Cuddalore town the SIPCOT (State Industrial Promotion Corporation of Tamil Nadu Limited) industrial complex is located on a sprawling 700 acres. In this industrial complex, nearly 70 industries manufacturing dyes, chemicals, pesticides and pharmaceuticals are functioning. The untreated and partially treated effluents from these industries are released into the river. Further, effluent from a large thermal power plant located upstream of the river also finds its way into the river. The river also receives municipal wastes and domestic sewage from in and around Cuddalore town and also wastes from many coconut husk retting units.

2.2 Sampling stations

From the study area, three sampling stations were selected on the backside of the SIPCOT industrial complex along the river and the latitude and longitude for each of the stations was found out and marked.

i) Station I - (Sothikuppam) - N 11º42’11.4” E 079º46’18.6”

ii) Station II - (Thaikal Thonithurai) - N 11º 39’28.0” E 079º44’59.7”

iii) Station III - (Near estuary) - N 11º42’11.8” E 079º46’18.3”.

2.3 Sampling and analysis

Samples were the representative of water to be tested. The samples were collected from the three sampling stations at regular intervals of 15 days for a span of 120 days from February 2010 to May 2010. The physico - chemical parameters were analyzed by following the standard procedures given in APHA (1995).

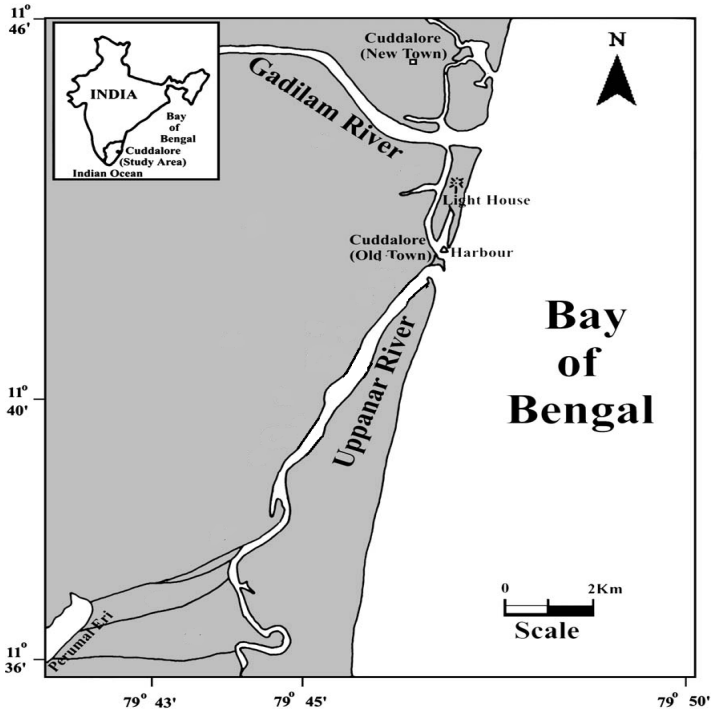

Figure 1 Study area - Uppanar River, southeast coast of India

2.4 Dispersion model

Several experimental studies in the hydrosphere are carried out to determine the velocity and longitudinal dispersion coefficient in rivers using the one-dimensional advection-diffusion equation (Fischer, 1973) expressed as

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - u\frac{\partial C}{\partial z} \qquad (1)$$

where C is the concentration, *D* is the longitudinal or axial dispersion coefficient, uniquely characterizes the degree of backmixing during flow and u is the mean flow velocity. In dimensionless form where z = (x/L) and $\theta = (t/\tau)$ the basic differential equation representing this dispersion model becomes

$$\frac{\partial C}{\partial \theta} = \left(\frac{D}{uL}\right)\frac{\partial^2 C}{\partial z^2} - \frac{\partial C}{\partial z} \qquad (2)$$

where, the dimensionless group (*D*/uL), called the dispersion number is the parameter which measures the extent of longitudinal dispersion (Levenspiel, 1991). In this case, different boundary conditions can be assumed. For open–open boundary conditions, an analytical solution exists. The C curves are given by

$$C_\theta = \frac{1}{2\sqrt{\pi(D/uL)}}\exp\left[\frac{(1-\theta)^2}{4(D/uL)}\right] \qquad (3)$$

and exclusively contains (D/uL) as variable parameter.

2.5 Dispersion number (D/uL)

In the present work, the data on the measured concentration of DO, nitrate and reactive silica were used for calculation of (D/uL). Levenspiel (1991) has introduced a parameter called dispersion number (D/uL), and it measures the extent of the longitudinal dispersion. The parameter (D/uL) can be evaluated from the experimentally recorded mean value and variance as suggested by Levenspiel (1991). The mean value or the centroid of the distribution is defined as

$$\tau = \frac{\int_o^\infty tCdt}{\int_o^\infty Cdt} \qquad (4)$$

The next most important descriptive quantity is the spread of distribution. This is commonly measured by the variance, σ^2, which is defined as

$$\sigma^2 = \frac{\int_o^\infty t^2 C dt}{\int_o^\infty C dt} - (\tau)^2 \qquad (5)$$

For hydraulically open system, dispersion σ_θ^2 can be calculated from the relationship

$$\sigma_\theta^2 = \frac{2D}{uL} + 8\left(\frac{D}{uL}\right)^2 \qquad (6)$$

where
D-Longitudinal dispersion coefficient (m^2/s)
u-Mean flow velocity through the river (m/s)
L-Length of the river (m)

2.6 Average percentage error

The average percentage error (APE) used to make quantitative analysis on the theoretical results is defined as follows (Mullai *et al.*, 2011a)

$$APE = \frac{1}{n}\sum_{i=1}^{n} \frac{|X_{1(i)} - X_{2(i)}|}{X_{1(i)}} * 100\% \qquad (7)$$

where X_1 and X_2 = observed and theoretical result sets

n = Number of observations

3. RESULTS AND DISCUSSION

3.1 Experimental dissolved oxygen, nitrate-nitrogen and reactive silica

Dissolved oxygen (DO) in water depends on the physical, chemical and biological activities in the water body. During the study period, along the three sampling stations I, II and III, the observed maximum and minimum DO concentrations were 8.72 and 3.01 mg/l, respectively. The record of maximum DO values might be due to the capacity of water to hold oxygen and the cumulative effect of higher wind velocity coupled with heavy rainfall and the resultant freshwater mixing (Mullai et al., 2011 b; Nayak et al., 2004; Sankar et al., 2010). The minimum value of DO registered could be attributed to the high rate of oxygen consumption by oxidizable mater found in the municipal wastes. Further, lesser input of freshwater and loss of oxygen to the atmosphere at higher temperatures led to low DO in the Uppanar River. Gasim et al. (2007) in their research work reported similar observations.

Distribution of nutrients was mainly based on the season and freshwater inflow from land sources. In general, nitrates represent the final product of biochemical oxidation of ammonia. Maximum nitrate content in any water body indicates their polluted nature (Sharma and Kansal, 2011). The nitrate-nitrogen concentration in the Uppanar River ranged from 1.23-33.9 µg/l for the three sampling stations I, II and III (Figure 2b). The higher concentration registered might be due to rain shower, decomposition of organic matter and leaching of nitrate from nearby agricultural field (Umamaheshwari and Saravanan, 2009). It might also be due to the river runoff, input of fertilizers and organic materials from the catchment areas during ebb tides. The lower nitrate value recorded might be due to utilization by phytoplankton for their photosynthetic activity. The present finding is in agreement with the work of Nayak et al. (2004) and Joshi et al. (2009) on different water bodies.

The reactive silica concentration in the Uppanar River ranged from 1.38 to 38.38 mg/l during the study period (Figure 2c). The record of higher reactive silica concentration might be due to heavy inflow of monsoonal fresh water derived from land drainage carrying silicate leached out from rocks. The lower values registered could be adduced to reduction in the freshwater input and uptake of silicate by phytoplankton for their biological activities. In addition to phyto-

plankton uptake processes, the absorption and co-precipitation of soluble silicon might also govern the distribution of dissolved reactive silica in the riverine environment (Sundaramanickam et al., 2008; Sankar et al., 2010).

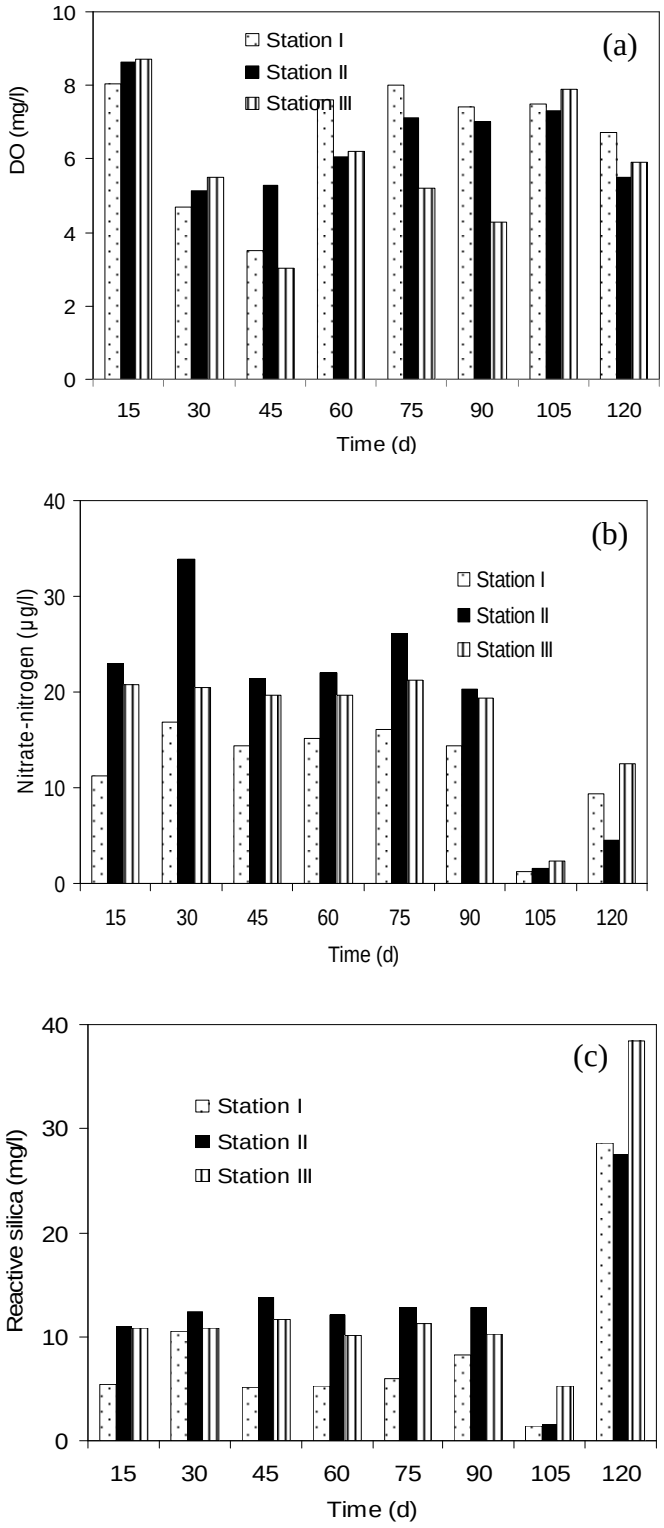

Figure 2 Variations of DO (a); Nitrate nitrogen (b); Reactive silica (c); at three sampling stations in the Uppanar River

3.2 Application of dispersion model

3.2.1 Theoretical dissolved oxygen, nitrate-nitrogen, reactive silica and dispersion number

Using the dispersion model, Eq. (3), the distributions of DO, nitrate-nitrogen and reactive silica in Uppanar River were predicted. The efficacy of the dispersion model is tested by comparing it with the measured field data. A comparison of E curves obtained by field data and dispersion model is given in Figures 3a-11a. In all the cases predicted E curve peak was slightly higher over the experimental E curve barring, E curve obtained for DO data at station III. Moreover, performance of the model in all the three different stations for the parameters studied, such as, DO, nitrate-nitrogen and reactive silica was ascertained by evaluating the scatter between the experimental and theoretical results by employing coefficient of multiple determination (R^2). The coefficient of multiple determination (R^2) was calculated based on the linear regression.

The normalized E curves (i.e., the area under the curve was unity) for the experimental DO, nitrate-nitrogen and reactive silica along the three sampling stations I, II and III, are depicted in Figures 3a-11a in dimensionless forms as functions of the dimensionless time and concentration. Using the normalised data, it is easy to predict and compare with different experimental results. The DO maximum peak recorded at station I was lower than the registered at stations II and III, indicating that full mixing was not attained. But, the shape of the DO pulses in all three stations was similar and produced a long "tail" which might be attributed to irregular shape of the riverbed, which might produce water dead zones (Albert et al., 1999; Rutherford, 1994). The obtained E curves for nitrate-nitrogen (Figures 6a-8a) and reactive silica (Figures 9a-11a) were similar to that of E curves obtained for DO (Figures 3a-5a).

The predicted minimum and maximum DO concentrations were 3.26 and 8.48 mg/l, respectively. The values of correlation coefficient of the dispersion modelling were high i.e., R^2 = 0.9992, 1.0 and 0.9983 for stations I, II and III, respectively (Figures 3b, 4b and 5b). The theoretical nitrate-nitrogen concentration ranged from 0.62-11.08 µg/l and that of reactive silica concentration varied from 1.08-22.50 mg/l for the three sampling stations. The correlation coefficient values obtained between the predicted and observed nitrate-nitrogen values for the stations I, II and III were 0.9998, 1.0 and 0.9987, respectively (Figures 6b-8b). Figures 9b, 10b and 11b represent the correlation coefficient of the dispersion modelling, R^2 = 1.0, 0.9942 and 1.0 for stations I, II and III, respectively between experimental and theoretical reactive silica values. The obtained correlation coefficient (R^2) values suggested that the model performed well. From Figures 3b to 11b, it could be inferred that the model became "closer" to the real system. It was also observed that there is a one to one correlation among the experimental and theoretical values.

3.3 Dispersion number (D/uL)

The experimentally calculated values of dispersion number (D/uL) at station I, station II and station III obtained for DO were 0.122, 0.136 and 0.152, for nitrate-nitrogen, 0.142, 0.136, and 0.163 and for reactive silica 0.114, 0.129 and 0.116, respectively (Table 1). As the dispersion numbers are less than 0.2, it is concluded that longitudinal dispersion is predominant in all the three stations studied.

The theoretically calculated values of dispersion number (D/uL) at station I, station II and station III obtained for DO were 0.127, 0.132 and 0.148, for nitrate-nitrogen, 0.142, 0.136, and 0.131 and for reactive silica 0.140, 0.124 and 0.0916, respectively (Table 1). The

longitudinal dispersion coefficient in rivers depends on several factors, such as, river discharge, mean depth, shear velocity, channel width and dead zones. In the present study, dispersion coefficient was estimated from dispersion number, which is the model parameter. The estimated dispersion coefficient of Uppanar River was compared with other rivers (Table 2). The results indicate that the model is feasible and can be used to predict the distribution of other pollutants.

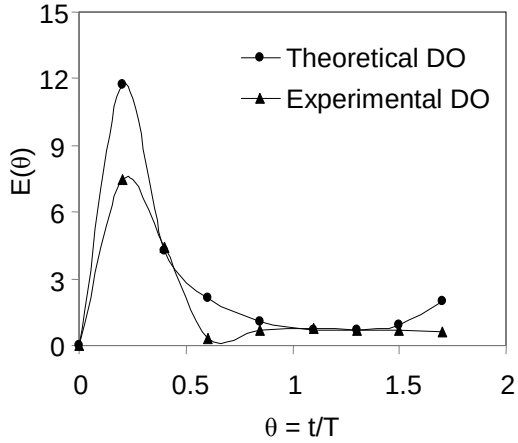

Figure 3a Theoretical and experimental E curves for DO concentrations at station I

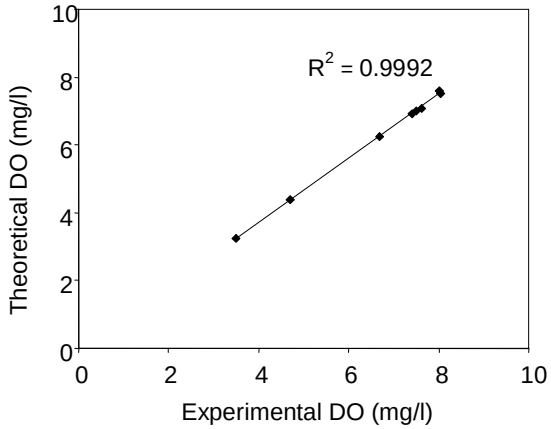

Figure 3b Validation of correlation between the theoretical and experimental DO at station I

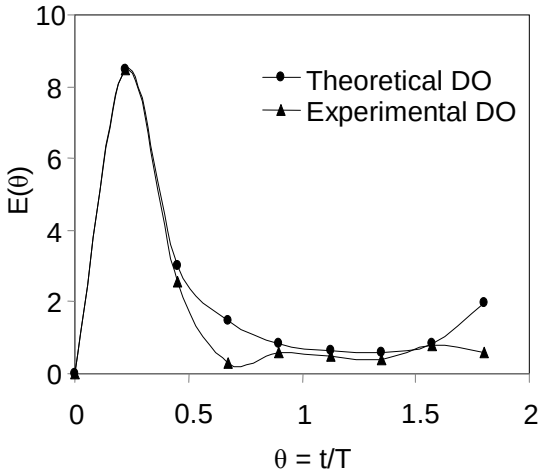

Figure 4a Theoretical and experimental E curves for DO concentrations at station II

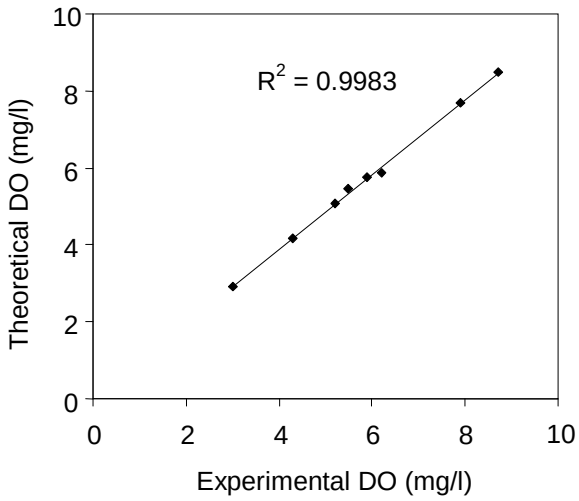

Figure 4b Validation of correlation between the theoretical and experimental DO at station II

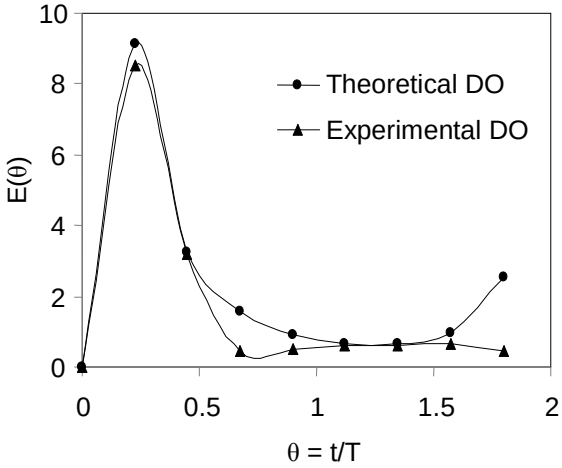

Figure 5a Theoretical and experimental E curves for DO concentrations at station III

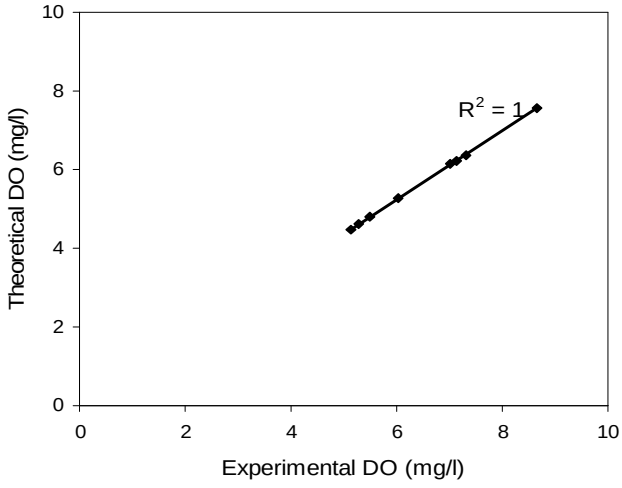

Figure 5b Validation of correlation between the theoretical and experimental DO at station III

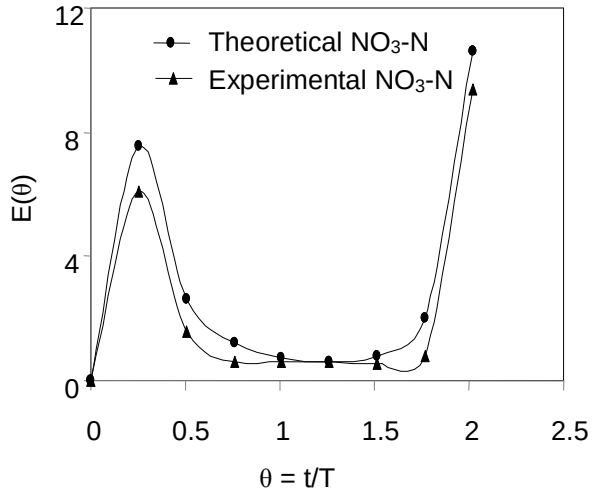

Figure 6a Theoretical and experimental E curves for NO_3-N concentrations at station I

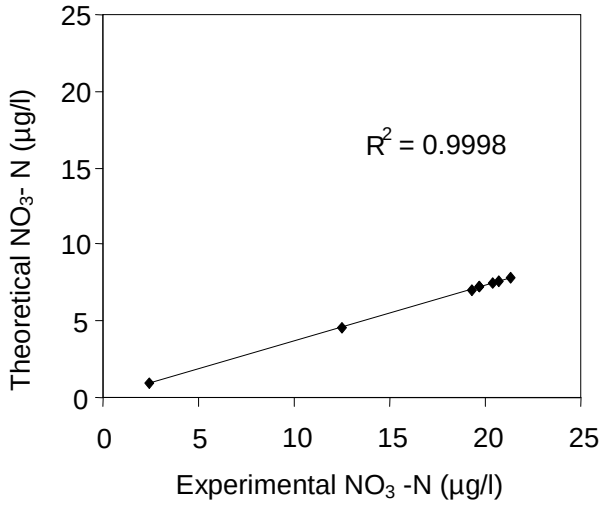

Figure 6b Validation of correlation between the theoretical and experimental NO_3-N at station I

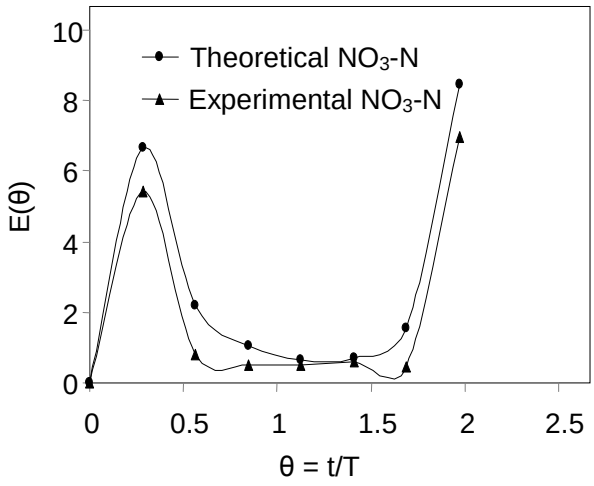

Figure 7a Theoretical and experimental E curves for NO_3-N concentrations at station II

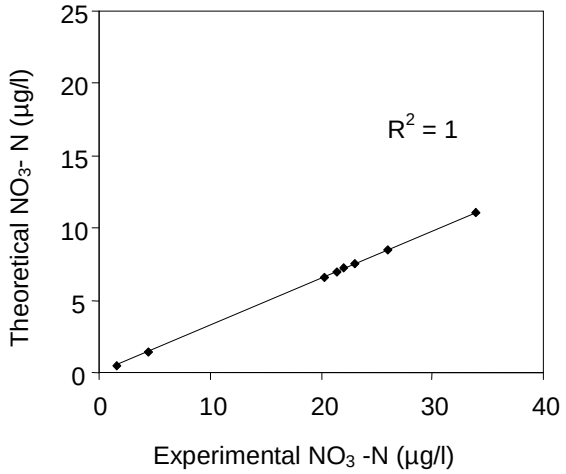

Figure 7b Validation of correlation between the theoretical and experimental NO_3-N at station II

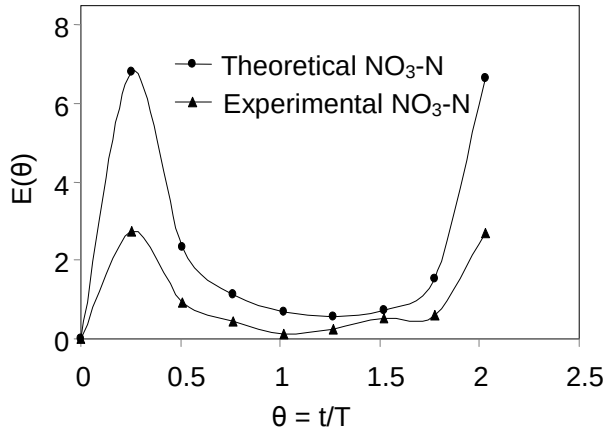

Figure 8a Theoretical and experimental E curves for NO_3-N concentrations at station III

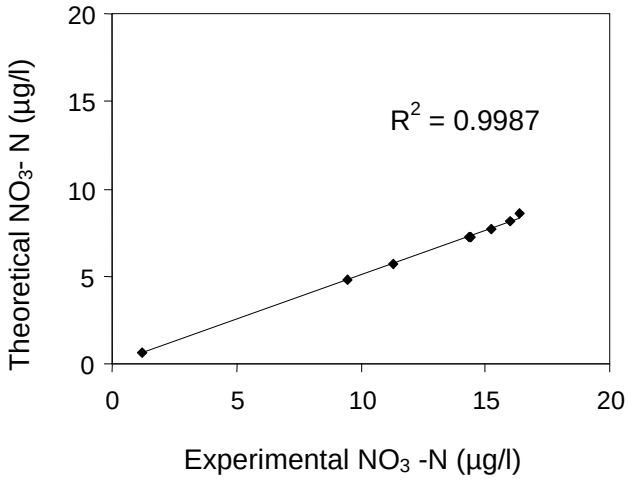

Figure 8b Validation of correlation between the theoretical and experimental NO_3-N at station III

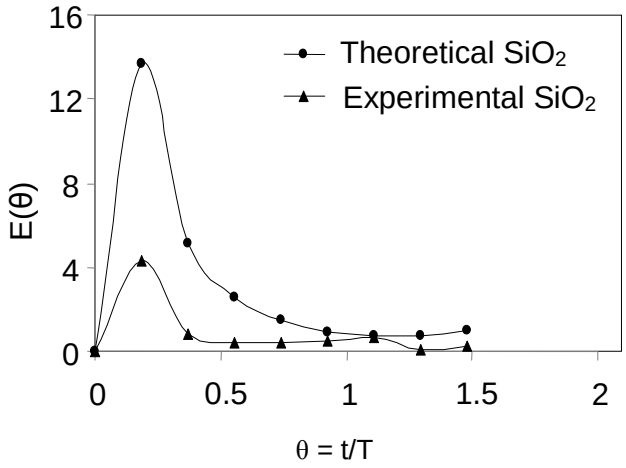

Figure 9a Theoretical and experimental E curves for SiO_2 concentrations at station I

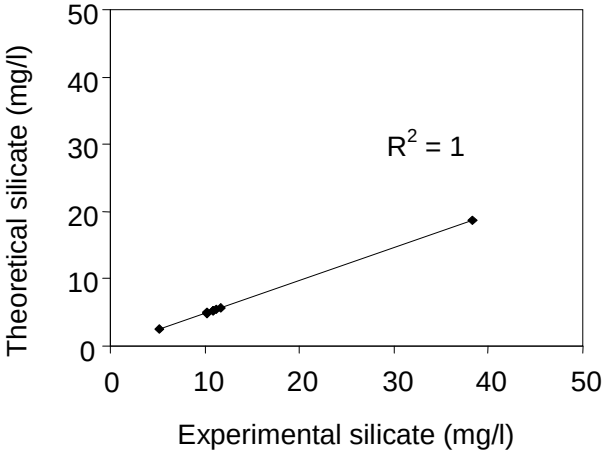

Figure 9b Validation of correlation between the theoretical and experimental SiO_2 at station I

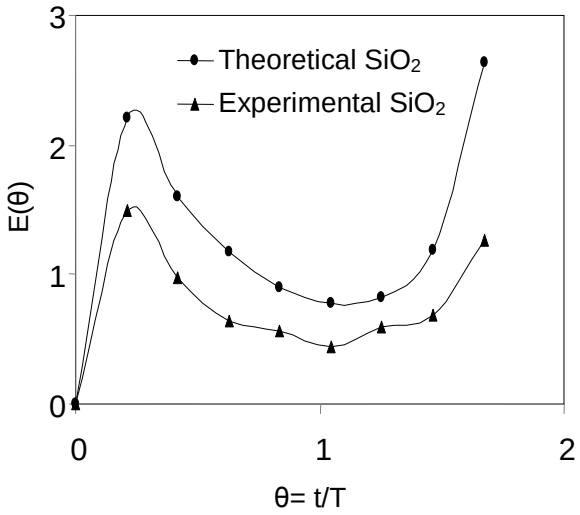

Figure 10a Theoretical and experimental E curves for SiO_2 concentrations at station II

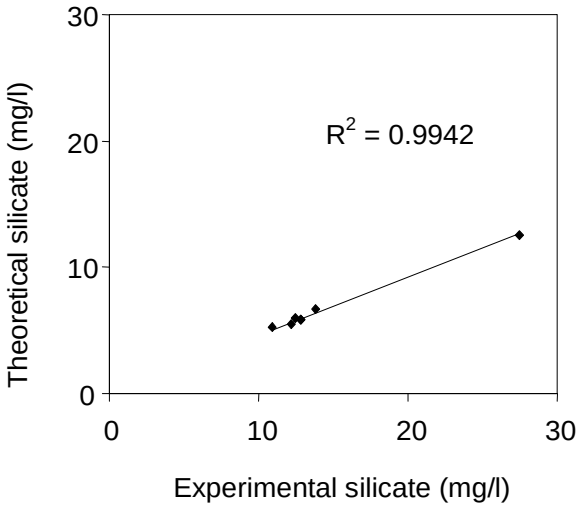

Figure 10b Validation of correlation between the theoretical and experimental SiO_2 at station II

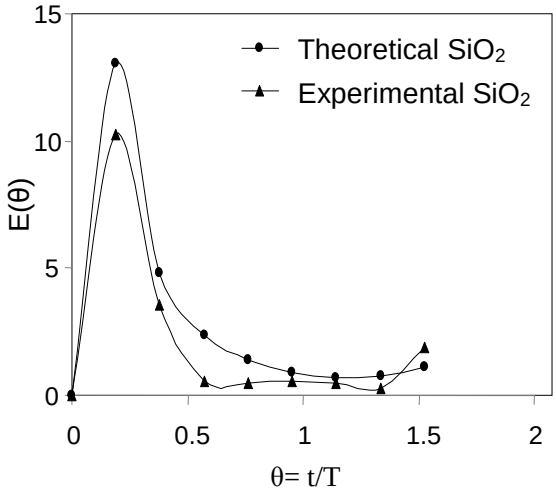

Figure 11a Theoretical and experimental E curves for SiO_2 concentrations at station III

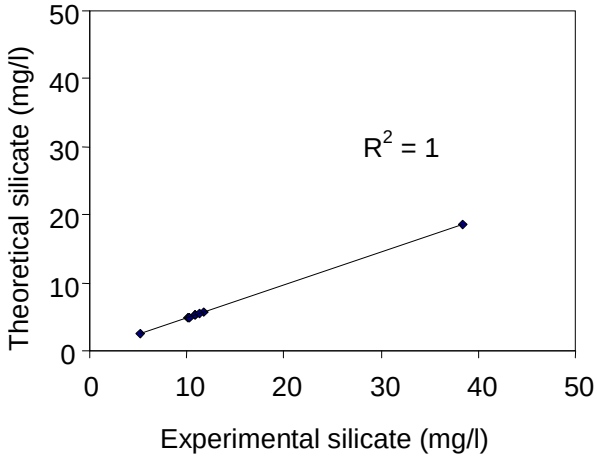

Figure 11b Validation of correlation between the theoretical and experimental SiO_2 at station III

Table 1 Comparison of experimental and theoretical dispersion numbers (D/uL)

Parameter	(D/uL) experimental	(D/uL) theoretical
DO-Station I	0.122	0.127
DO-Station II	0.136	0.132
DO-Station III	0.152	0.148
Nitrate-Station I	0.142	0.142
Nitrate-Station II	0.136	0.136
Nitrate-Station III	0.163	0.131
Reactive silica-Station I	0.114	0.140
Reactive silica -Station II	0.129	0.124
Reactive silica -Station III	0.116	0.0916

Table 2 Comparison of longitudinal dispersion coefficients for different rivers (data from Albert et al., 1999)

River	Mean depth (m)	Mean width (m)	Mean velocity (m/s)	Dispersion coefficient (m^2/ s)
Missouri	2.70	200	1.55	1500
Sabine	2.04	104	0.58	316
Yadkin	2.33	70	0.43	111
Ebro	2.4-3.0	120-140	0.56-1.28	41-392
Uppanar	1.626	95	0.49	132 (Present study)

3.4 Average percentage error

According to Eq. (7), the calculated values of average percentage error at station I, station II and station III obtained for DO were 6.56, 12.72 and 2.85 %, for nitrate-nitrogen, 63.37, 67.39 and 49.27 % and for reactive silica, 21.59, 53.45 and 51.53 %, respectively. The closer the average values of APE is to zero, the better the model fits the time-series (Margoni and Psilovikos, 2010; Mullai *et al.*, 2011 b). As the APE values were high, more experimental data are required to increase the validity of the proposed model.

CONCLUSIONS

The appraisal of water quality of Uppanar River is of immense significance for improving living standard and quality of life in that region. Prediction of the DO, nitrate-nitrogen and reactive silica in Uppanar River was carried out experimentally as well as by the application of dispersion model. The result showed a good agreement with the measured concentrations. The measured data will be utilized as a basis for an assessment of actual state of pollution in the river. The dispersion coefficient determined by a selected kind of pollutants could also be used to predict the dispersion processes of other kinds of pollutants, if the pollutant dispersion mechanism is assumed the same. For the modelled experimental data, the statistical quality of the dispersion modeling was high for stations I, II and III, between experimental and theoretical

DO, nitrate-nitrogen and reactive silica values. The results of this work could be used to predict the movement and dispersion of a soluble substance in the Uppanar River and might permit to design adequate surveillance programs and emergency actions in the case of the accidental release of a soluble or hazardous substance.

ACKNOWLEDGEMENTS

The authors gratefully thank the authorities of the Annamalai University, India for their help and the Ministry of Environment and Forests, New Delhi, India for financial support (F. No. 19-09/2006-RE dated 30.06.2009).

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