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A new Fuzzy-LOGIC based Model for Chlorophyll-a in Pulicat Lagoon, India

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ABSTRACT: Coastal lagoons are complex ecosystems exhibiting a high degree of non-linearity in the distribution and exchange of nutrients dissolved in the water column due to their spatio-temporal characteristics. This factor has a direct influence on the concentrations of chlorophyll-a, an indicator of the primary productivity in the water bodies as lakes and lagoons. Moreover the seasonal variability in the characteristics of large-scale basins further contributes to the uncertainties in the data on the physico-chemical and biological characteristics of the lagoons. Considering the above, modelling the distributions of the nutrients with respect to the chlorophyll-concentrations, hence requires an effective approach which will appropriately account for the non-linearity of the ecosystem as well as the uncertainties in the available data. In the present investigation, fuzzy logic was used to develop a new model of the primary production for Pulicat lagoon, Southeast coast of India. Multiple regression analysis revealed that the concentrations of chlorophyll-a in the lagoon was highly influenced by the dissolved concentrations of nitrate, nitrites and phosphorous to different extents over different seasons and years. A high degree of agreement was obtained between the actual field values and those predicted by the new fuzzy model (d = 0.881 to 0.788) for the years 2005 and 2006, illustrating the efficiency of the model in predicting the values of chlorophyll-a in the lagoon.

Key words: Coastal lagoon, Pulicat lagoon, Chlorophyll-a, Fuzzy logic, Multiple Regression analysis

INTRODUCTION

From the past, several studies have been undertaken till date to understand the complex physico-chemical cum biological characteristics of coastal lakes and lagoons (Praveena *et al.,* 2008; Priju and Narayana, 2007; Mensi *et al.,* 2008) and their inter-relationships, and the different techniques are available to model their biogeochemical interactions. However, since successful interpretation of scientific data on lagoons is critical for designing an effective modelling approach, it is imperative to utilise the available scientific knowledgebase on lakes and lagoons to build a methodology to model the lagoon characteristics to aid in the effective management these intriguing coastal ecosystems.

The use of simple ecological models in assessing the status of ecosystems as lakes and lagoons has been abundantly recorded in the scientific literature over the past centuries. The earliest of these approaches was by Lotka (1925) and Volterra (1926) who expressed change in a single population as a function of a constant birth rate and death rate. Riley (1947) had, by the use of a model of an ecosystem, projected changes in the herbivores per unit biomass as the sum of a constant assimilation balance against temperature dependant respiration, carnivorous predation and the natural mortality of that system. Further, Riley (1946) had created a coupled model to calculate steady state plankton population levels for North Atlantic Ocean.

Empirical budgeting approaches have also been popular with researchers worldwide. Most widely used approach is the budgeting proposed by the budgeting node of Land-Ocean Interaction in Coastal Zone (LOICZ) of the International Geosphere-Biosphere Programme (IGBP). With the biogeochemical modelling guidelines developed by LOICZ (Gordon *et al.,* 1996) to implement nutrient budgets, several reports of applications of the model have been available describing the testing and use of the approach for CNP (Carbon Nitrogen Phosphorus) budgets in estuarine and coastal systems (Smith & Crossland, 1999; Smith *et al.,* 1999, Dupra *et al.,* 2000a & b). In the Indian scenario, Girija et al. (2005) had described the development of a two-dimensional depth-averaged hydrodynamic model and simulation of the currents and salinity corresponding to monsoonal regime as well as lagoon mouth conditions for Chilika lagoon in

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India. More recently, Gupta et al. (2006) provided the budgets of nitrogen and phosphorus constructed using LOICZ approach for Muthupet lagoon.

However, despite recounting the experiences of modelling coastal lagoons from various researchers worldwide, these studies have at the same time, indicated the need for realistic and simple models of ecosystem for unique coastal ecotones such as lagoons. For example, in their study of the role of carbonate dissolution in determining the complex dynamics of dissolved inorganic carbon in estuarine ecosystems such as Gautami - Godavari estuary, Bouillon et al. (2003) had indicated that at least a simple and reliable nutrient budgeting of the coastal zone was necessary for quantifying the changes in the biogeochemistry and productivity of the coastal ecosystems.

At present, a complete study of the various sources of external inputs and internal transformation in a coastal lagoon in connection with its productivity is, at large, a subject that requires greater introspection in India. Given the multi-faceted role of a coastal lagoon as an socio-economic lifeline, an eco-cultural entity as well as a environmental laboratory for research, modelling the biology and hydro-chemical characteristics, albeit a necessary component for sustainable management of these resources, remains an gargantuan scientific quest with little direction and lots of uncertainties.

However, modelling the ecosystem status and predicting productivity within large basins of high spatio-temporal and seasonal variability is the greatest challenge at present for the modellers. While different modelling techniques are available to represent these ecosystems, their applicability is often limited to those systems having similar conditions to the range of data prescribed in these models (Soyupak and Chen, 2004). Further, these empirical or statistical models do not consider the spatio-temporal aspects of the lagoons. Rast et al (1983) carried out an assessment of the predictive power of the available simple empirical models for primary productivity and found that the predicted values of the chlorophyll-a were within a factor of ± 3 in all lakes.

Dynamic water quality modelling software such as CE-QUAL is more accurate, and includes the spatio-temporality of the lagoons as a factor in modelling. Using differential equations, they help to investigate the relationships between the physico-chemical or biological mechanisms. But these involve expensive and time-consuming data collection as well as extensive numerical calculation (Soyupak and Chen, 2004) in which the potential for error is greater with increasing complexity in calculation. Hence, the combination of uncertainty in data and complexity in calculation may give erroneous results.

In the past few years, soft computing techniques, such as fuzzy logic, neural networks and cellular automata that are capable of handling the uncertainty in data and analysis have been used in ecosystem modelling (*Rene and Saidutta, 2008; Nakane and Haidary, 2010*; Tuzkaya and Gulsun, 2008). Fuzzy logic systems can be used to model non-linear relationships easily and effectively even when only limited data is available (Silvert, 1997). Fuzzy rules provide a common-sense description of the action of the system and the information in a fuzzy-logic system are processed in terms of fuzzy sets defined through an associated membership function. The ability of the fuzzy logic systems, being universally approximators and also well –defined functions mapping real-value input to real-value output has made them powerful tools for exploring complex non-linear biological problems in the context of an ecosystem.

MATERIALS & METHODS

The study area for the present investigation is situated near the village of Pulicat Town, located about 60 km from Chennai city (Fig. 1). It is a coastal inland water embayment in the form of a lagoon, known as the Pulicat lagoon, which is the second largest brackish water lake in India. Geographically the coastal lagoon is situated between latitudes 13° 25′– 13° 55′ N and longitudes 80° 03′ – 80°19′ E with and an altitude of 0-10 m (Azariah, 1988). The lagoon is a cross-boundary ecosystem extending between the neighbouring states of Andhra Pradesh (AP) and Tamil Nadu (TN). According to WWF report (1993), about 84% of the Pulicat Lake ecosystem lies in AP. It occupies a total area 650 km^2 with a high tide water spread area of about 178 m^2 (Rao and Rao, 1975). The entire lake is a huge evaporating basin and has been known to fall 3.9 feet below the mean sea level during April – May and June. The lake is about 60 km in length and 0.2 to 17.5 km in width. The total area of about 72,000 ha includes about 20,000 ha (27.7%) of swamps to north of the lake. It has a high water spread area of 460 Km and low water spread area of 250 Km. The seawater enters the lake through two bar mouths located at the north and south ends of the lagoons (WWF, 1993). The lake is shallow with an average depth of about 1.5 m; the maximum depth being 9.0 m near the entrance to the sea. The lake is separated from the Bay of Bengal by an inland spit called the Sriharikota Island, which is currently used as a launching pad of India's space research programme. The main source of fresh water

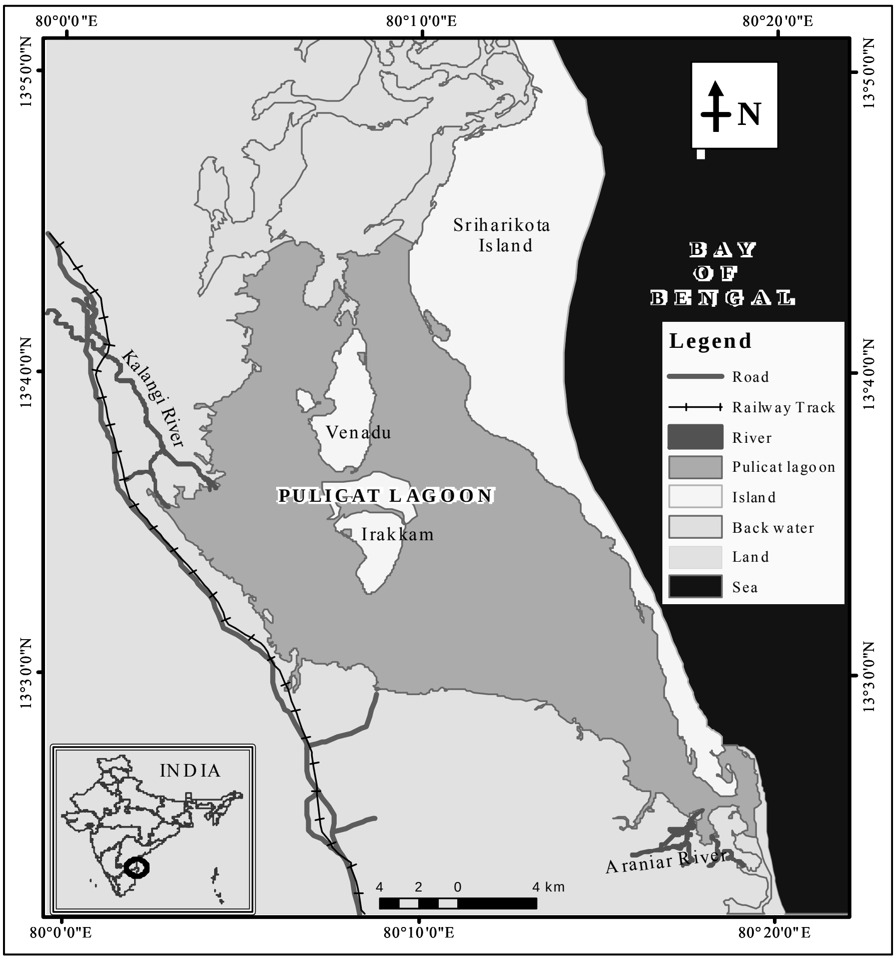

Fig. 1. Study Area

to the lake is due to the run-off by 3 seasonal rivers, which open into the lake. Of these rivers, river Arani flows at its southern side and Kalangi (Chacko et al., 1953; Rao and Rao, 1975) at its mid western region while Swarnamukhi scarcely joins the northern end of the lagoon. Fresh water input is effective only during the North East monsoon (October to December). The species composition and hydrobiology of Pulicat lagoon are well documented from earlier investigations (Krishnan and Sampath, 1972; ENVIS Report, 2001; Ramesh and Ramachandran, 2002 and Rema Devi *et al.,* 2004) which provide specific information on its characteristics.

Pulicat lagoon and its environs serve as a good feeding and breeding ground for a variety of aquatic and terrestrial birds. About 16 island villages and a total of 97 other villages adjoining the water body are directly or indirectly dependent on the it for their livelihood. The lagoon supports a rich biodiversity of high biomass of fish, prawn, crustaceans and plankton, which form the principle source of food for the birds. An estimated number of 15,000 flamingos and other birds like grey pelicans, painted storks, grey herons, ducks, teals, terns, herons, gulls, a number of waders and several other migratory water birds have been reported to visit Pulicat every year (Azariah, 1988). Despite the availability of data on the characteristics of the lagoon, a comprehensive modelling study for representing the lagoon status is hitherto lacking. The present investigation hence assumes the importance of providing the first modelling study aimed to represent the primary productivity of the lagoon considering the influence of the other physico-chemical factors that influence the lagoon production.

Water samples collected from 12 sampling points in Pulicat lagoon (Fig. 2) in the years 2005 and 2006 were analyzed for the following physico-chemical parameters Water Temperature, Extinction Coefficient (Secchi disk depth), Dissolved Oxygen, bicarbonate, Calcium, Chloride, Silicate, Ammonia Nitrogen, Nitrite Nitrogen, Nitrate Nitrogen and Inorganic Phosphate

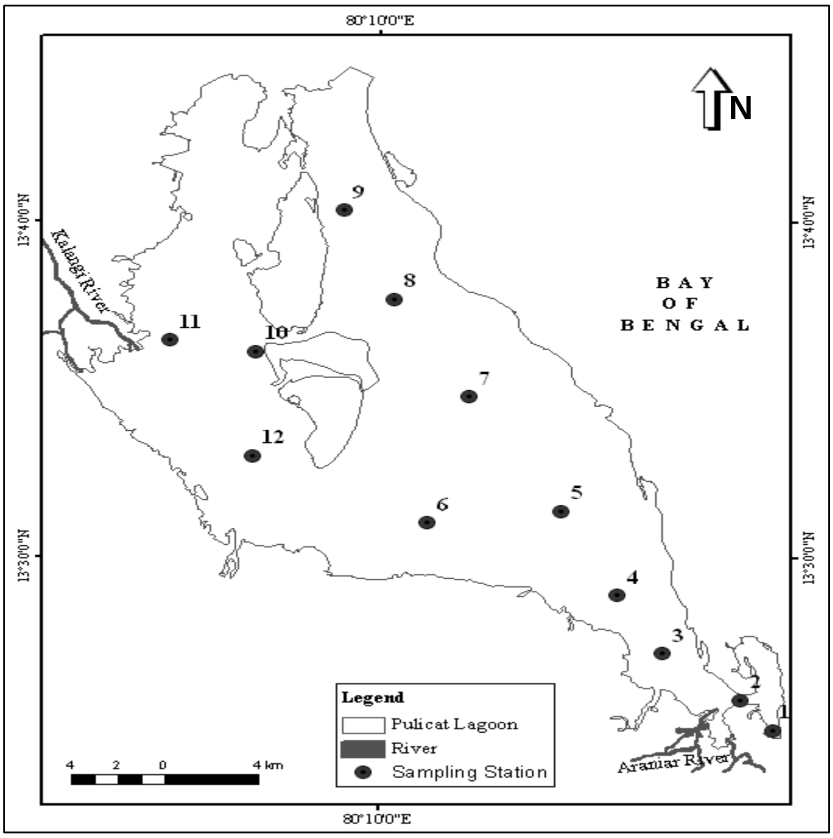

Fig. 2. Sampling Locations in Pulicat Lagoon

along with chlorophyll-a according to the methods for analyses described in Strickland and Parsons (1965). The data on water quality was used to determine the relationships of these physico-chemical parameters to the productivity of the lagoon (represented by chlorophyll-a) using in two steps –

1. Constructing a multiple regression model (to identify the important factors influencing chlorophyll-a production in the lagoon) and,
2. Using fuzzy logic to construct a fuzzy model to determine the chlorophyll-a concentrations in the lagoon.

For this modelling study, the data on the water quality for the years 2005 and 2006 were used. For the selection of the variables for fuzzy modelling, a multiple regression analysis was performed as follows. Soyupak and Chen (2004) had constructed a multiple regression model assuming that chlorophyll-concentrations could be modelled as linearly dependant to the measured water quality parameters.

These water quality variables exhibit high temporal variability from season to season for any sampling station. Since the system is very large the observations for any season can be assumed as representing pseudo steady state conditions within that season. The chlorophyll-a concentrations can be modelled as linearly dependent to the measured water quality variables if classical multiple regression model assumption is considered as applicable. The same assumption is adopted in the present study and a multiple regression model (Equation 1) in the following form was used to calculate the concentrations of chlorophyll-a from the concentrations of the water quality parameters:

$$y = (Chl\text{–}a) \qquad (1)$$

$$= a_0 + a_1 Temp + a_2 ExtCoeff +$$

$$a_3 Depth + a_4 pH + a_5 salinity +$$

$$+ a_6 DO + a_7 HCO_3 + a_8 Ca + a_9 Cl$$

$$+ a_{10} SiO_3 + a_{11} NH_4 +$$

$$+ a_{12} NO_2 + a_{13} NO_3 + a_{14} PO_4 + \varepsilon$$

Where,
a_i (i = 0-14) are the regression coefficients,
ε is the error term which is normally distributed (ε ~ N(0,σ^2),
Temp = Temperature (°C)
ExtCoeff = Extinction Coefficient (m)
DO = Dissolved Oxygen (mL/L)
HCO_3 = Bicarbonate (mg/L)
Ca = Calcium (mg/L)
Cl = Chloride (mg/L)
SiO_3 = Silicate (mg/L)
NH_4 = Ammoniacal Nitrogen (µg/L)
NO_2 = Nitrite Nitrogen (µg/L)
NO_3 = Nitrate Nitrogen (µg/L)
PO_4 = Phosphate (µg/L)

For the regression equation to be valid to be used for predictions, it must reflect the regression model for the population. The regression statistics including the Multiple R (used to measure the strength of the relationship between the independent variables and dependent variable); the R Square, Adjusted R Square and the Standard Error were obtained from the analyses and are summarized in Tables 1 to 4 along with the Analysis of Variance (ANOVA) table. From the ANOVA table, the F-statistic and the significance F are used to test the validity of the regression. In the present study relationships between the physico-chemical parameters of water quality derived from earlier analyses were used to formulate the fuzzy rules which describe these complex inter-relationships in logical statements. The observed values were normalised to a scale of 0 to 1 for fuzzification using the Fuzzy Logic Toolbox of MATLAB 7.0 software. This process yielded the fuzzy memberships functions (FMF) that defined how each point in the input space was mapped to a membership value (also called the 'degree of membership' denoted as'd' between 0 and 1.

Table 1. Summary Of the Output for Multiple Regression Analysis For Post Monsoon Season

Regression Statistics	
Multiple R	0.826621717
R Square	0.683303462
Adjusted R Square	0.190664404
Standard Error	0.009439559

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	14	0.001730279	0.000123591	1.387026567	0.316285563
Residual	9	0.000801947	8.91053E-05		
Total	23	0.002532227			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Significance*
Intercept	-0.010	0.257	-0.040	0.969	-
Temperature	0.003	0.007	0.419	0.685	N
Extinction Coefficient	-0.008	0.011	-0.728	0.485	N
Depth	0.003	0.019	0.146	0.887	N
pH	0.001	0.010	0.075	0.942	N
Salinity	-0.001	0.002	-0.643	0.536	N
DO	0.003	0.008	0.404	0.696	N
Bicarbonate	0.000	0.000	0.751	0.472	N
Calcium	0.000	0.000	1.278	0.233	N
Chloride	0.000	0.000	-1.001	0.343	N
Silicate	0.000	0.000	0.796	0.447	N
Ammonia-N	0.000	0.000	0.731	0.483	N
Nitrite-N	0.001	0.001	0.605	0.560	N
Nitrate-N	0.000	0.000	-0.297	0.773	N
Phosphate-P	0.000	0.000	-0.913	0.385	N

Significant / most influential variables: none

Table 2. Summary of the output for multiple regression analysis for summer season

Regression Statistics	
Multiple R	0.907401565
R Square	0.823377601
Adjusted R Square	0.548631646
Standard Error	0.01146902

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	14	0.005518847	0.000394203	2.996868876	0.05139974
Residual	9	0.001183846	0.000131538		
Total	23	0.006702693			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Significance*
Intercept	-0.436	0.352	-1.240	0.246	-
Temperature	0.012	0.010	1.212	0.257	N
Extinction Coefficient	-0.020	0.022	-0.917	0.383	N
Depth	-0.108	0.057	-1.893	0.091	Y
pH	-0.015	0.008	-1.952	0.083	Y
Salinity	0.003	0.001	2.304	0.047	Y
DO	0.013	0.010	1.222	0.253	N
Bicarbonate	0.000	0.000	1.007	0.340	N
Calcium	0.000	0.000	-2.837	0.019	Y
Chloride	0.000	0.000	2.318	0.046	Y
Silicate	0.000	0.000	-2.945	0.016	Y
Ammonia-N	0.000	0.000	0.781	0.455	N
Nitrite-N	-0.003	0.001	-3.416	0.008	Y
Nitrate-N	0.000	0.000	-1.034	0.328	N
Phosphate-P	0.000	0.000	0.378	0.714	N

Significant / most influential variables: Depth, pH, Salinity, Calcium, Chloride, Silicate ions, Nitrite-N

If X is the input space containing the different parameters and its elements are denoted by x, then a fuzzy set Ain X is defined as a set of ordered pairs represented in a general form as:

$$A = \{x, \mu_A(x) \mid x \in X\} \quad (2)$$

Where,
$\mu_A(x)$ = the fuzzy membership function (FMF) of x in A. This FMF (Equation 2) maps each element of X containing the observed field values of all environmental parameters in the present study to a membership value between 0 and 1. In this way, fuzzy membership values (FMV) for each parameter for different stations and seasons over two years 2005 and 2006 were obtained by applying the FMFs and these values were used in the development of the various fuzzy models in the present investigation.
The Fuzzy Logic Toolbox of MATLAB 7.0 software was used for the analyses in which the fuzzy decision rules are determined by the choice of the FMFs. The general form of a fuzzy decision rule has been shown in below in Equation 3:

IF
Temp is <L> or <H> or <M> or <E>, ExtCoeff is <L> or <H> or <M> or <E>, Depth is <L> or <H> or <M> or <E>, DO is <L> or <H> or <M> or <E>, Salinity is <L> or <H> or <M> or <E>, HCO_3 is <L> or <H> or <M> or <E>, Ca is <L> or <H> or <M> or <E> , Cl is <L> or <H> or <M> or <E>, SiO_3 is <L> or <H> or <M> or <E>, NH_4 is <L> or <H> or <M> or <E>, NO_2 is <L> or <H> or <M> or <E>, NO_3 is <L> or <H> or <M> or <E> , PO_4 is <L> or <H> or <M> or <E>,
THEN
y_1 = [<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> TEMP] + (3)
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> DO] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> Depth] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> ExtCoeff] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> Salinity] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> HCO_3] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> Cl] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> Ca] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> SiO_3] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> NH_4] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> NO_3] +

Table 3. Summary of the output for multiple regression analysis for pre monsoon season

Regression Statistics	
Multiple R	0.894500129
R Square	0.800130481
Adjusted R Square	0.489222339
Standard Error	0.012477878

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	14	0.005609681	0.000400692	2.573526949	0.078763567
Residual	9	0.001401277	0.000155697		
Total	23	0.007010958			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Significance*
Intercept	0.196	0.463	0.423	0.682	-
Temperature	-0.010	0.011	-0.910	0.386	N
Extinction Coefficient	-0.007	0.099	-0.070	0.946	N
Depth	0.014	0.080	0.170	0.869	N
pH	0.013	0.010	1.275	0.234	N
Salinity	-0.006	0.003	-2.148	0.060	Y
DO	-0.008	0.006	-1.353	0.209	N
Bicarbonate	0.000	0.000	-1.459	0.179	Y
Calcium	0.000	0.000	1.616	0.141	Y
Chloride	0.000	0.000	2.724	0.023	Y
Silicate	0.000	0.000	1.241	0.246	N
Ammonia-N	0.000	0.000	-0.841	0.422	N
Nitrite-N	0.000	0.001	0.757	0.468	N
Nitrate-N	0.000	0.000	-0.219	0.832	N
Phosphate-P	0.000	0.000	1.734	0.117	Y

Significant / most influential variables: Salinity, Bicarbonate, Calcium, Chloride, Phosphate-P

[<fmv_L> or <fmv_H> or <fmv_M> or <fmv_E> NO_2] +
[<fmv_L> or <fmv_H> or <fmv_M> oe <fmv_E> PO_4]

Where,
<fmv> denoted the fuzzy membership values of the respective fuzzy parameters to be the estimated,
L = Low membership value
H = High membership value
M= Medium membership value
E = Extreme membership value

In this manner a set of fuzzy rules were derived and the membership values for chlorophyll-a were derived using these rules. These were subjected to the process of defuzzification for fuzzy reasoning. The 'min' operator was applied to the fuzzy membership functions (FMF) from each rule as given below (Equation 4):
For Rule i (i = 1 to n) :

$$W_{i,t} = \min [FMV(Temp, A_i) + FMV(DO, A_i) + FMV(SAL, A_i) + \ldots\ldots + FMV(PO, A_i)] \quad (4)$$

Where, A_i is the fuzzy set defined in the 'If' part of the Rule i (i = 1 to 16).
For each rule the modelled value of y is calculated by the 'Then' part of the rule base and the final output of the fuzzy model is defuzzified using the weighted average as given in Equation 5 :

$$y_{i,t} = \frac{\sum_{i=1}^{N} w_{i,t} y_{i,t}}{\sum_{i=1}^{N} w_{i,t}} \quad (5)$$

The results of the multiple regression analyses and the fuzzy model have been summarized in the following section under Results and discussions.

RESULTS & DISCUSSION

In general it is understood from the results of the ANOVA obtained, that if the calculated F is higher than the significance F, the null hypothesis can be

Table 4. Summary of the output for multiple regression analysis for monsoon season

Regression Statistics	
Multiple R	0.82788733
R Square	0.685397431
Adjusted R Square	0.196015658
Standard Error	0.005065188

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	14	0.000503053	3.59324E-05	1.400537308	0.310885417
Residual	9	0.000230905	2.56561E-05		
Total	23	0.000733958			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Significance*
Intercept	-0.407	0.221	-1.846	0.098	-
Temperature	0.016	0.008	2.050	0.071	Y
Extinction Coefficient	-0.003	0.001	-1.983	0.079	Y
Depth	0.005	0.005	0.906	0.388	N
pH	-0.007	0.005	-1.436	0.185	Y
Salinity	0.004	0.002	1.618	0.140	Y
DO	0.004	0.003	1.430	0.187	Y
Bicarbonate	0.000	0.000	1.349	0.210	N
Calcium	0.000	0.000	-0.232	0.822	N
Chloride	0.000	0.000	-1.707	0.122	Y
Silicate	0.000	0.000	1.203	0.260	N
Ammonia-N	0.000	0.000	-1.466	0.177	Y
Nitrite-N	0.000	0.000	0.352	0.733	N
Nitrate-N	0.000	0.000	0.459	0.657	N
Phosphate-P	0.000	0.000	0.598	0.565	N

Significant / most influential variables: Temperature, Extinction Coefficient, pH, Salinity, DO, Chloride,Ammonia-N

rejected and it is then concluded that at least one of independent variable is correlated to the dependent variable. In the present study, the calculated F (shown in the Tables 1 to 4) is high and significance F values are all close to zero, therefore, the null hypothesis has been rejected and it was concluded that at least one of the independent variable explains the variations in the dependent variable. Thus the validity of the multiple regression models was verified. The analysis of the residuals for homogeneity also indicated that the model is valid and therefore we can perform a statistical test for the significance of the regression variables which is summarized in Tables 1 to 4.

Hence, from these tables, the following variables were considered influential and were focused upon for the model development - Depth, pH, Salinity, Calcium, Chloride, Silicate ions, Nitrite-N, Bicarbonate, Phosphate, Temperature, Extinction Coefficient, DO, Ammonia-N. As mentioned in the methodology, the fuzzy model for predicting the chlorophyll-concentrations was constructed and the results obtained were analysed from which the major trends observed in the relationship between chlorophyll a and the other parameters were inferred. The trends in the chlorophyll-a distribution obtained from the model indicate that the productivity of the algal biota in the lagoon is influenced by the amount of available nutrients in the water column, the temperature of the water and the depth of the water column. Further, the results obtained showed that the chlorophyll–a production was highly influenced by seasonal concentrations of dissolved oxygen, nitrates, nitrites, phosphates and ammonia. The performance of the model has been discussed below. Tables 5 and 6 show the differences between the observed and predicted values of chlorophyll-concentrations for the years

Table 5. Observed and predicted values of chlorophyll-a concentrations from fuzzy model for the year 2005

Sampling Stations	Post monsoon		Summer		Pre monsoon		Monsoon	
	Predicted Values (µg/L)	Observed values (µg/L)	Predicted Values (µg/L)	Observed values (µg/L)	Predicted Values (µg/L)	Observed values (µg/L)	Predicted Values (µg/L)	Observed values (µg/L)
1	0.12	0.40	0.19	0.34	0.23	0.28	0.16	0.70
2	0.00	0.25	0.90	0.30	0.45	0.22	0.25	0.57
3	0.55	0.36	0.87	0.30	0.10	0.26	0.11	0.37
4	0.00	0.01	0.14	0.32	0.22	0.21	0.23	0.57
5	0.00	0.28	0.18	0.33	0.21	0.25	0.27	0.37
6	0.11	0.32	0.25	0.35	0.26	0.28	0.24	0.48
7	0.18	0.34	0.19	0.34	0.27	0.29	0.17	0.74
8	0.45	0.39	0.25	0.35	0.23	0.32	0.17	0.41
9	0.32	0.37	0.56	0.39	0.58	0.31	0.24	0.40
10	0.08	0.31	0.79	0.41	0.89	0.27	0.27	0.84
11	0.02	0.24	0.13	0.32	0.12	0.22	0.2	0.37
12	0.14	0.33	0.14	0.32	0.08	0.28	0.09	0.31

Table 6. Observed and predicted values of chlorophyll-a concentrations from fuzzy model for the year 2006

Sampling Stations	Post monsoon		Summer		Pre monsoon		Monsoon	
	Predicted Values (µg/L)	Observed values (µg/L)	Predicted Values (µg/L)	Observed values (µg/L)	Predicted Values (µg/L)	Observed values (µg/L)	Predicted Values (µg/L)	Observed values (µg/L)
1	0.14	0.32	0.11	0.37	0.21	0.31	0.23	0.72
2	0.05	0.19	0.70	0.33	0.22	0.25	0.21	0.59
3	0.70	0.29	0.27	0.33	0.12	0.29	0.19	0.39
4	0.02	0.04	0.1	0.35	0.13	0.24	0.1	0.59
5	0.03	0.30	0.11	0.36	0.19	0.28	0.16	0.39
6	0.60	0.33	0.21	0.38	0.15	0.31	0.23	0.50
7	0.19	0.34	0.13	0.37	0.17	0.32	0.16	0.76
8	0.23	0.39	0.19	0.38	0.27	0.35	0.17	0.43
9	0.16	0.37	0.44	0.42	0.34	0.34	0.15	0.42
10	0.17	0.24	0.32	0.44	0.33	0.30	0.90	0.86
11	0.09	0.23	0.11	0.35	0.27	0.25	0.18	0.39
12	0.12	0.31	0.12	0.35	0.19	0.31	0.1	0.33

2005 and 2006. In order to evaluate the model performance, a statistical measure called the 'degree of agreement' has been used to determine the extent to which the model predictions are error free. Degree of agreement is a statistical measure of model performance advocated by Willmot (1982) and Willmot *et al.*, (1985). The value of the degree of agreement (d) is reflects the degree to which the observed variant is accurately estimated by the simulated variant. In the present case, it determines the degree

Table 7. Degree of agreement between predicted values from fuzzy model and observed values of chlorophyll-a

SEASON	YEAR	DEGREE OF AGREEMENT (d)
POST MONSOON	2005	0.854
	2006	0.881
SUMMER	2005	0.840
	2006	0.835
PRE MONSOON	2005	0.876
	2006	0.856
MONSOON	2005	0.799
	2006	0.788

of match between the observed and predicted chlorophyll-a concentration. Being a standardised measure,'d' can be easily interpreted and cross-comparisons of its magnitudes for a variety of models regardless of units can be easily made (Willmot, 1982). It varies between 0 and 1, in which a computed value of 1 indicates perfect agreement between the observed and predicted observations, while 0 denotes complete disagreement. In the present study, the degree of agreement (d) was calculated using the following formula provided in Equation 6:

$$d = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}[|P_i - \overline{O}| + |O_i - \overline{O}|]^2} \qquad (6)$$

Where,
d = Degree of agreement,
P_i = Predicted value or simulated variate
O_i = Observed value or variate
$\bar{O}$ = Average of observed values
N = number of observations

Table 7 shows the degree of agreement (d) between the predicted chlorophyll-a from water quality variables with the observed values. The value of d was found to range between 0.876 to 0.788 over the different seasons and years. In general, the performance of the model (Table 7) is found to be higher in the year 2005 (d = 0.876 to 0.799) than in 2006 (d = 0.881 to 0.788). The highest degree of agreement between the observed and predicted values was observed in the post-monsoon (0.854 and 0.881 in 2005 and 2006 respectively) and pre-monsoon seasons (0.876 and 0.856 in 2005 and 2006 respectively). The performance of the model for the summer and monsoon seasons was found to be lower when compared to the post-monsoon and pre-monsoon periods. This is an interesting point to be noted as it is clear from the present investigation that the seasonal distribution of the nutrients and chlorophyll-a being highly non-linear, cannot be modelled using a formalised approach strictly as a mathematical or numerical approach.

CONCLUSION

The present investigation indicates that the productivity of the algal biota in the lagoon as evidenced by the production and distribution of chlorophyll-an in Pulicat lagoon, was highly influenced by seasonal concentrations of dissolved oxygen, nitrate and nitrite nitrogen, phosphates and ammonia present in the dissolved form in the water. The present investigation has hence highlighted the important factors affecting the primary production of the lagoon, which is important to a coastal manager aiming for sustainable resource utilisation of the lagoon.

The modelling attempt described in the present study has proven the efficiency in the use of fuzzy logic to model non-linear relationships of ecosystem parameters easily and effectively even when only limited data is available. From the results of the present study, it is clear that the non-linearity in the distribution of the nutrients (which in turn affect the productivity of the lagoon) definitely play an important factor in affecting the model performance and only when this aspect of multi-environmental ecosystems as coastal lagoons is considered while modelling, can the results obtained give a reasonable and meaningful picture. Thus, the present investigation has highlighted the effectiveness of logic-based model such as the one developed presently in modelling a complex environment as coastal lagoons.

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