Nutrient modeling for a semi-intensive IMC pond: an MS-Excel approach

Lala I. P. Ray, B. C. Mal and S. Moulick

ABSTRACT

Semi-intensive Indian Major Carp (IMC) culture was practised in polythene lined dugout ponds at the Aquacultural Farm of Indian Institute of Technology, Kharagpur, West Bengal for 3 consecutive years at three different stocking densities (S.D), *viz*., 20,000, 35,000 and 50,000 numbers of fingerlings per hectare of water spread area. Fingerlings of *Catla, Rohu* and *Mrigal* were raised at a stocking ratio of 4:3:3. Total ammonia nitrogen (TAN) value along with other fishpond water quality parameters was monitored at 1 day intervals to ensure a good water ecosystem for a better fish growth. Water exchange was carried out before the TAN reached the critical limit. Field data on TAN obtained from the cultured fishponds stocked with three different stocking densities were used to study the dynamics of TAN. A developed model used to study the nutrient dynamics in shrimp pond was used to validate the observed data in the IMC pond ecosystem. Two years of observed TAN data were used to calibrate the spreadsheet model and the same model was validated using the third year observed data. The manual calibration based on the trial and error process of parameters adjustments was used and several simulations were performed by changing the model parameters. After adjustment of each parameter, the simulated and measured values of the water quality parameters were compared to judge the improvement in the model prediction. Forward finite difference discretization method was used in a MS-Excel spreadsheet to calibrate and validate the model for obtaining the TAN levels during the culture period. Observed data from the cultured fishponds of three different S.D were used to standardize 13 model parameters. The efficiency of the developed spreadsheet model was found to be more than 90% for the TAN estimation in the IMC cultured fishponds.

Key words | forward finite difference discretization method, IMC cultured pond, model efficiencies, total ammonia nitrogen, water quality

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INTRODUCTION

Composite fish culture or polyculture of indigenous carp together has been found to result in high fish production in freshwater ponds in India (Lakshmanan *et al.* 1971; Chakrabarty *et al.* 1972a, 1972b; Singh *et al.* 1972; Sinha *et al.* 1973). Freshwater aquaculture in India mostly involves polyculture of three Indian Major Carps (IMC), *viz*., catla (*Catla catla* Hamilton), rohu (*Labeo rohita* Hamilton) and mrigal (*Cirrhinus mrigala* Hamilton). IMC is one of the most important groups of fish cultured in the Indian subcontinent and accounts for more than 95% of the world production (Kalla *et al.* 2004). Higher growth rates and yields can be derived from polyculture as compared to monoculture as a result of both complementary and synergistic interactions among the fish species (Yashouv 1971; Hepher *et al.* 1989; Milstein 1992; CIFA 2006; Ray 2014; Rathor *et al.* 2016). To obtain high growth rates in intensive aquaculture, formulated diets have a vital role in meeting the nutritional requirements of the target species. Protein constitutes an important component of the diet of fish because it determines growth (Kalla *et al.* 2004).

Intensive aquaculture is facing criticism for unsustainable practices (Naylor *et al.* 1998, 2000). The regular practice includes in this intensive culture is the discharge

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of pond waters high in nutrients and phytoplankton with the potential to cause eutrophication of waterways. There is an increasing demand to understand the natural processes in pond ecosystems to reduce discharge loads and improve water quality (Tacon 1996; Burford *et al.* 2001; Jory *et al.* 2001). Nitrogen (N) plays a key role in the dynamics of aquaculture systems due to its dual role, in various forms, as a nutrient and as a toxicant. N dynamics in intensive aquaculture ponds have been studied using mathematical modeling by several researchers (Hargreaves 2006; Lorenzen 1997; Lefebvre *et al.* 2001; Moulick *et al.* 2011). Hargreaves (2006) and Jiménez-Montealegre *et al.* (2002) modeled total ammonia N (TAN) re-mineralization as a constant or temperature-dependent sediment flux without considering the dynamics of N in the sludge. Nitrogen input is deposited directly as uneaten feed or faeces (Burford & Williams 2001; Jagadeesh *et al.* 2013; Majhi & Rasal 2014; Das *et al.* 2015; Safi *et al.* 2016). Part of the sludge N is re-mineralized to enter the water column again as TAN. Such recycled N may account for the bulk of TAN input into the water column late in the production cycle (Burford & Longmore 2001). Ray *et al.* (2008) proposed that intensely stocked fishponds need water exchange. This fish pond wastewater is a viable source to supplement irrigation water to the crop as well as bridge the gap of chemical fertilizer requirement, especially nitrogen to a marginal amount. In the present study, an already developed model was used and solved in a user friendly spreadsheet platform.

MATERIALS AND METHODS

Nine rectangular dugout ponds were constructed with an average depth of 1.5 m and 150 m^2 of water spread area at the experimental farm of Aquacultural Engineering discipline, Indian Institute of Technology, Kharagpur, West Bengal, India. The field experiments represent a typical upland condition prevailing in the eastern Indian region. It is located at a latitude of 22° 19′ N and longitude of 87° 19′E with an altitude of 48 m above the mean sea level. All the ponds were lined with 150 gsm, 250 μ thick, UV ray protected blue colour polyethylene sheets. Below the lining material, 30 cm thickness of sand cushioning was provided to avoid rupture of the polythene lining. Polythene sheet was spread on the bottom and sides, including the embankment and was buried outside the embankment in a soil layer of 30 cm thickness. Over the lining, loamy soil was provided to a depth of 30 cm to provide a suitable environment for the growth of phytoplankton and zooplankton to be used by the fish as natural feed. A schematic diagram of the experimental layout is shown in Figure 1.

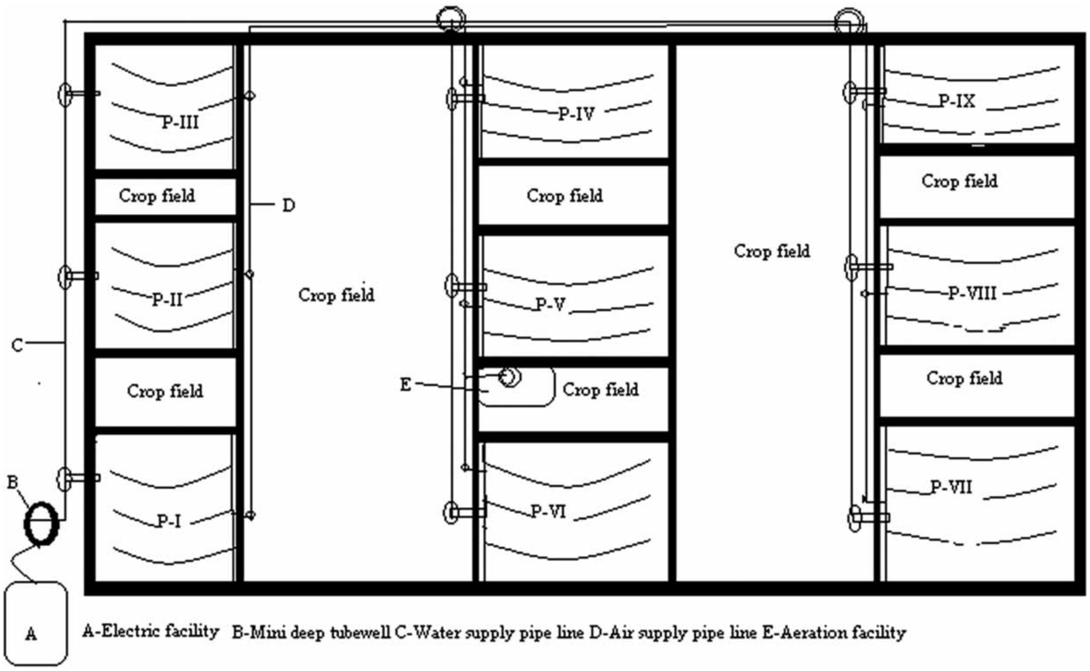


Figure 1 | Schematic layout of the experimental field.

Fish were stocked at three different stocking densities (S.D), *viz*., 20,000, 35,000 and 50,000 numbers per hectare of water spread area at a stocking ratio of 4:3:3 for rohu catla and mrigal. Three different S.Ds constituted three treatments and three levels of replication were maintained for this experiment. The nomenclature of the various experimental ponds (P-I, P-II, P-III, P-IV, P-V, P-VI, P-VII, PVIII and P-IX) are as follows (Figure 1):

P-I, P-II and P-III: 20,000 numbers of fish per hectare of water spread area
P-IV, P-V and P-VI: 35,000 numbers of fish per hectare of water
P-VII, P-VIII and P-IX: 50,000 numbers of fish per hectare of water.

The water quality parameters of the fish ponds were monitored at 1 day intervals for all the nine fish ponds. Based on the critical limit of total ammonia nitrogen (TAN), water exchange was performed from the fish ponds. A conceptual model of the nitrogen build up in the system is shown in Figure 2.

A mathematical model to investigate the nitrogen dynamics in intensive shrimp culture pond was formulated by Burford & Lorenzen (2004). In the present study, a user friendly spreadsheet was developed to solve the model expressions. In this model, the source for N input is assumed to be solely from the formulated feed. The inflow to the fish pond consisted of water supplied from rainfall and supplemental filling of the fish pond by groundwater through pipe lines during water exchange.

Outflow included actual evaporation, water withdrawal for irrigation and a very small amount of seepage. To overcome N build up in the pond, water exchange was performed so that the water quality parameters of pond water could be under an acceptable limit for IMC. The process of denitrification was ignored, as many studies showed it to be negligible. Nitrogen can also enter the water column as TAN from IMC excretion or through sediment mineralization of uneaten feed or through the re-mineralization of wasted feed and as dissolved organic N (DON).

Theoretical consideration

TAN may be transformed *via* a number of pathways: assimilated by phytoplankton (CHL), volatilized as gaseous ammonia, converted to nitrite and nitrate (NOX) *via* nitrification processes or discharged during water exchanges. Nitrate may in turn be assimilated by phytoplankton or discharged during water exchanges. In this model, the denitrification process was ignored, as many studies showed it to be negligible. The DON content is produced in significant quantities in fish ponds as a result of the addition of feed. However, much of it is refractory and not readily utilized by the natural biota, and, therefore, is shown as an isolated pool in the model.

Conceptually, the functional relationship is expressed as:

$$TAN \alpha F(NOX, DON, CHL) \tag{1}$$

The conceptual model presented in Equation (1) has five state variables representing the main N components: TAN, NOX, DON, NSED and particulate N in the form of phytoplankton, expressed as units of CHL. Nitrogen dynamics model is given by the following set of coupled differential

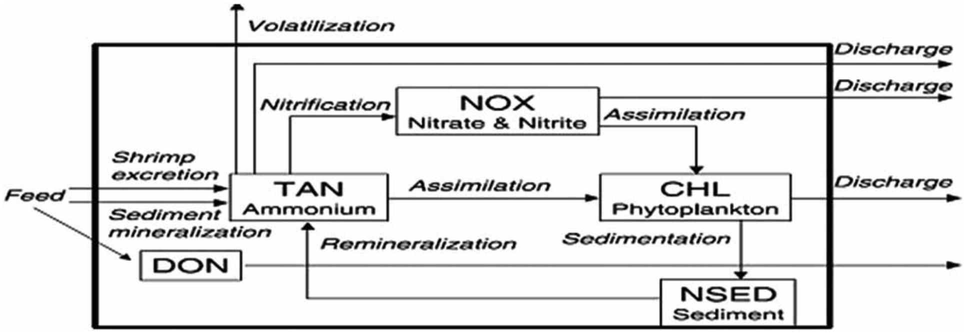


Figure 2 | Conceptual model of N input, transformation and removal in intensive pond (*Source:* Burford & Lorenzen 2004). TAN: Total ammonia nitrogen; NOX: Nitrogen oxides in the form of NO_2 and NO_3; CHL: Chlorophyll; NSED: Nitrogen in sediment and DON: Dissolved organic nitrogen.

equations for the five state variables:

$$\frac{dC_{TAN}}{dt} = qA_t + rM_{NSED} - (n + v + f)C_{TAN} - gcC_{CHL}\left[\frac{C_{TAN}}{(C_{TAN} + C_{NOX})}\right] \tag{2}$$

$$\frac{dC_{NOX}}{dt} = nC_{TAN} - fC_{NOX} - gcC_{CHL}\left[\frac{C_{NOX}}{(C_{TAN} + C_{NOX})}\right] \tag{3}$$

$$\frac{dC_{CHL}}{dt} = gcC_{CHL} - (f + s)C_{CHL} \tag{4}$$

$$\frac{dM_{NSED}}{dt} = scC_{CHL} - rM_{NSED} \tag{5}$$

$$\frac{dC_{DON}}{dt} = (1 - q)A_t - fC_{DON} \tag{6}$$

where C_{TAN} = TAN concentration (mg L^{-1}); t = time (day); q = proportion of N waste entering the water as TAN (with the remainder entering the water as DON); A_t = total N waste input per unit time (mg L^{-1} day^{-1}); r = re-mineralization rate of TAN in the mud of pond bottom (day^{-1}); M_{NSED} = mass of N (mg) in the sludge per L of pond water; n = nitrification rate (day^{-1}); v = volatilization rate of ammonia (day^{-1}); f = water exchange rate (day^{-1}); g = phytoplankton growth rate (day^{-1}); c = N/CHL ratio of phytoplankton; C_{NOX} = NOX concentration (mg L^{-1}); C_{CHL} = CHL concentration (mg L^{-1}); s = sedimentation rate of phytoplankton (day^{-1}); C_{DON} = DON concentration (mg L^{-1}). The total N waste input A_t was assumed to be proportional to the metabolism of the fish population and is given in Equation (7).

$$A_t = aN_tW_tb \tag{7}$$

where a = N waste produced by one fish per unit weight (mg g^{-1} day^{-1}); W_t = the mean weight of one fish (g); N_t = number of fish available in the pond t days after stocking and is given by an exponential mortality model (Equation (8)); and b = allometric scaling factor of metabolism.

$$N_t = N_0e^{-Mt} \tag{8}$$

where N_0 = initial stocking density (L^{-2}) and M = natural mortality rate (day^{-1}) of IMC. Fish mean weight W_t is given by Chen & Powers (1990) as a function of temperature as given in Equation (9).

$$W_t = [W_0^{1/3} + TGC \times T \times t]^3 \tag{9}$$

where W_0 = the weight at stocking (g), TGC = temperature growth coefficient, T = mean water temperature (°C) and t = time (day).

The growth rate (g) of phytoplankton is given by Equation (10).

$$g = g_{\max}L_{light}L_N \tag{10}$$

where $g_{\max}$ = maximum growth rate in the absence of limitation, (day^{-1}) and L_{light} and L_N = the light and TAN plus nitrate limitation coefficients, respectively. It was assumed that there was no phosphate deficiency which could limit the growth. The light limitation coefficient is given by the integral of Steele's light inhibition model over the water column, with light conditions defined by the Lambert-Beer law as per Equation (11).

$$L_{light} = \left(\frac{e}{k}\right) \times \left[\exp\left\{\left(\frac{-I_0}{I_{sat}}\right) \times \exp(-kz)\right\} - \exp\left(\frac{-I_0}{I_{sat}}\right)\right] \tag{11}$$

where I_0/I_{sat} = ratio of the surface light intensity to the saturating light intensity; k = the extinction coefficient (m^{-1}) and z = the pond depth (m). The extinction coefficient is the sum of extinction due to CHL and extinction due to other sources given by Equation (12).

$$k = k_{CHL}C_{CHL} + k_{other} \tag{12}$$

where k_{CHL} = extinction per unit CHL concentration (m^{-1} mg^{-1}) and k_{other} = extinction due to other sources. Nitrogen limitation is defined by the Michaelis-Menten model and is given by:

$$L_N = \frac{(C_{TAN} + C_{NOX})}{[(C_{TAN} + C_{NOX}) + k_{sN}]} \tag{13}$$

where k_{SN} = half-saturation constant for N (mg L^{-1}).

Phytoplankton was assumed to assimilate both TAN and NOX in proportion to their relative concentrations in the water column. Nitrification, volatilization, sedimentation, re-mineralization and discharge of N are described as the first-order rate process.

Model parameters

Model parameters for the intensive IMC culture adopted under the study are presented in Table 1.

Development of spreadsheet application using Microsoft Excel

Using forward finite difference technique and based on Equations (2)–(6), the following equations may be written as:

$$C_{TAN(i+1)} = C_{TAN(i)} + (t_{i+1} - t_i) \times \left[\begin{array}{l} (qaN_0e^{-Mt(i)}) \times \{(W_0^{1/3} + TGC \times T_i \times t_i)^3 \times b\} \\ +r \times C_{NSED(i)} - (n + v + f)C_{TAN(i)} \\ -g_{\max}(\exp(1)/k) \times \left[\exp\left\{\left(\frac{-I_0}{I_{sat}}\right) \times \exp(-kz)\right\} - \exp(I_0/I_{sat})\right] \\ \times\left\{\frac{(C_{TAN(i)} + C_{NOX(i)})}{[(C_{TAN(i)} + C_{NOX(i)} + K_{sN})]}\right\} \times c \times C_{CHL(i)}\left[\frac{C_{TAN(i)}}{C_{TAN(i)} + C_{NOX(i)}}\right] \end{array} \right] \tag{14}$$

$$C_{NOX(i+1)} = C_{NOX(i)} + (t_{i+1} - t_i) \times \left[\begin{array}{l} nC_{TAN(i)} - fC_{NOX(i)} - g_{\max}[(\exp(1)/k) \times \exp\{(-I_0/I_{sat}) \times \exp(-kz)\} - \exp(-I_0/I_{sat})] \\ \left\{\frac{(C_{TAN(i)} + C_{NOX(i)})}{(C_{TAN(i)} + C_{NOX(i)}) + K_{SN}}\right\} \times c \times C_{CHL(i)}\left(\frac{C_{TAN(i)}}{C_{TAN(i)} + C_{NOX(i)}}\right) \end{array} \right] \tag{15}$$

$$C_{CHL(i+1)} = C_{CHL(i)} + (t_{i+1} - t_i) \times \left[\begin{array}{l} g_{\max} \times \{(\exp(1)/k) \times \exp\{(-I_0/I_{sat}) \times \exp(-kz)\} - \exp(-I_0/I_{sat})\} \\ \times\left\{\frac{(C_{TAN(i)} + C_{NOX(i)})}{\left[(C_{TAN(i)} + C_{NOX(i)} + K_{sN})\right]}\right\} \times c \times C_{CHL(i)} - (f + s)C_{CHL(i)} \end{array} \right] \tag{16}$$

$$M_{NSED(i+1)} = M_{NSED(i)} + (t_{i+1} - t_i) \times \left\{scC_{CHL(i)} - rM_{NSED(i)}\right\} \tag{17}$$

$$C_{DON(i+1)} = C_{DON(i)} + (t_{i+1} - t_i) \times \left[(1-q)aN_0e^{-Mt(i)}\left\{W_0^{1/3} + (TGC \times T_i \times t_i)^3 \times b\right\} - fC_{DON(i)}\right] \tag{18}$$

Assuming $(t_{i+1} - t_i) = 1$ day and knowing the initial values of TAN, NOX, CHL, NSED and DON, the concentration values of the five state variables may be predicted at different times. To solve the equations simultaneously, Microsoft Excel was used.

Simulation, validation and efficiency of the developed model

Field data on TAN obtained from the cultured fish pond stocked with three different stocking densities were used to study the dynamics of TAN in cultured fishponds. Two years (Years 2006 and 2007) of observed TAN data were used to calibrate the spreadsheet model and the same model was validated using the 3rd year (Year 2008) observed data. Manual calibration based on the trial and error process of parameters adjustments was used and several simulations were performed by changing the model parameters. After adjustment of each parameter, the simulated and measured values of the water quality parameters were compared to judge the improvement in the model prediction.

Forward finite difference discretization method was used in a MS-Excel spread sheet to calibrate and validate the model for obtaining the TAN levels during the culture period. Two years' observed data from the cultured fish ponds of three different S.Ds were used to standardize thirteen (13) model parameters as presented in Table 1. The formulated model was later validated by using the observed values of the last year. The efficacy of the model was checked using three criteria: (i) root mean square error (RMSE), (ii) coefficient of determination (R^2) and (iii) Nash Sutcliffe index (E_{NS}) expressed as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(o_i - p_i)^2} \tag{19}$$

$$R^2 = \left(\frac{\sum_{i=1}^{N}(o_i - o_{avg})(p_i - p_{avg})}{\sqrt{\sum_{i=1}^{N}(o_i - o_{avg})^2}\sqrt{\sum_{i=1}^{N}(p_i - p_{avg})^2}}\right)^2 \tag{20}$$

$$ENS = 1 - \left[\frac{\sum_{i=1}^{N}(p_i - o_i)^2}{\sum_{i=1}^{N}(o_i - o_{avg})^2}\right] \tag{21}$$

Table 1 | Description about model parameters

Parameter	Unit
Portion of N entering fishpond water as TAN (q)	–
N waste produced by one fish per unit weight (a)	(mg g^{-1} day^{-1})
Allometric scaling factor of metabolism (b)	–
Extinction coefficient (k)	(day^{-1})
Extinction due to other sources (k_{other})	(m^{-1})
Extinction per unit chlorophyll concentration (k_{CHL})	(m^{-1} mg^{-1} L^{-1})
Natural mortality rate (M)	(day^{-1})
Re-mineralization rate of TAN in bottom mud (r)	(day^{-1})
Nitrification rate (n)	(day^{-1})
Volatilization rate of ammonia (υ)	(day^{-1})
Maximum growth rate in the absence of limitation (g_{max})	(day^{-1})
Ratio of N to chlorophyll in phytoplankton (c)	–
Half-saturation constant for N (K_{SN})	(mg L^{-1})

where $o_i = i^{th}$ observed value; $p_i = i^{th}$ predicted value; $o_{avg} =$ mean of the observed values; $p_{avg} =$ mean of the model predicted values and $N =$ total number of observations.

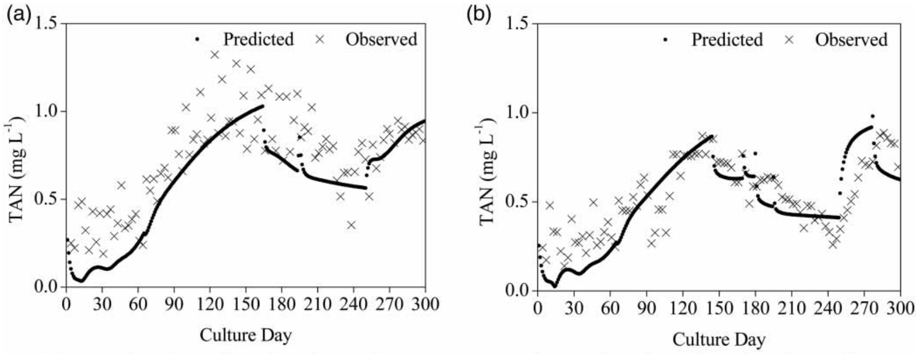
RESULTS AND DISCUSSION

Ammonia is toxic to fish and is considered to be a major factor limiting fish biomass in an intensive culture (Thurston & Russo 1983; Cai & Summerfelt 1992; Forsberg & Summerfelt 1992; Leung *et al.* 1999). During the mineralization process of organic N in pond soils, ammonia is released as a byproduct. In water, NH_3 (ammonia) and NH_4^+ (ammonium) are in equilibrium depending on pH and temperature (Timmons *et al.* 2002; Ray *et al.* 2009). The sum of these two forms is called total ammonia nitrogen (TAN). The concentration of ammonia increases in the pond ecosystem due to fish metabolism and decomposition of organic matter by bacteria (Walsh & Wright 1995). Although both NH_3 and NH_4^+ may be toxic to fish, unionized ammonia is the more toxic form (Körner *et al.* 2001; Colt 2006; Kumar *et al.* 2013).

The calibrated values of the model parameters based on the 2 year field data obtained from experimental ponds (P-I to P-IX) are presented in Table 2. These calibrated values of the model parameters were used in validating the last 1 year of data obtained from the same experimental ponds. The observed and predicted values of TAN in experimental ponds with S.D 2.0, 3.5 and 5.0 are shown in Figure 3(a)–3(c), respectively. It can be observed from the figures that the predicted data closely match with the observed data in all the cases. The calculated values of R^2, RMSE and E_{NS} were found to be 0.94, 0.20 and 0.92, respectively. This shows that the model gives a satisfactory response with respect to TAN for various stocking densities. Spreadsheet technique in formulating a model was also used to calibrate and validate shrimp pond TAN, nitrate, nitrite and also chlorophyll values (Moulick *et al.* 2011). The building up of TAN value prediction was tried by several workers using conceptual models (Lorenzen 1997), mathematical models (Burford

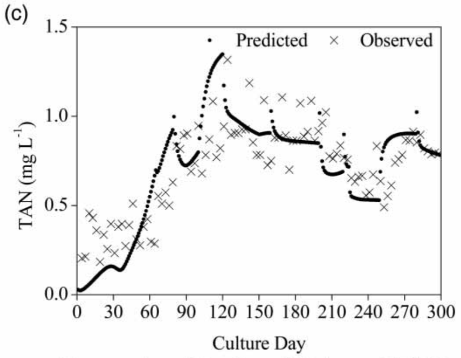
Table 2 | Calibrated values of the model parameters

Description of the parameters	Symbol	Value used in calibration	Source
Portion of N entering fish pond water as TAN	q	0.7	Otsuki & Hanya (1972)
N waste produced by one fish per unit weight	a	3.3	Machiels & Henken (1986)
Allometric scaling factor of metabolism	b	0.65	van Dam & Pauly (1995)
Extinction coefficient	k	0.0055	Scavia (1980)
Extinction due to other sources	k_{other}	3.0	Scavia (1980)
Extinction per unit chlorophyll concentration	k_{CHL}	11.0	Scavia (1980)
Natural mortality rate	M	0.0055	Experiment/Estimated
Remineralisation rate of TAN in bottom mud	r	0.06	Bansal (1976)
Nitrification rate	n	0.2	Bansal (1976)
Volatilization rate of ammonia	υ	0.05	Wolfe *et al.* (1986)
Maximum growth rate in the absence of limitation	g_{max}	1.4	Scavia (1980)
Ratio of N to chlorophyll in phytoplankton	c	3.2	Jørgensen *et al.* (1978)
Half-saturation constant for N	K_{SN}	0.03	Scavia (1980)



Observed and Predicted Values of TAN for Fishpond Water with S.D-2.0

Observed and Predicted Values of TAN for Fishpond Water with S.D-3.5



Observed and Predicted Values of TAN for Fishpond Water with S.D-5.0

Figure 3 | (a–c) Observed and predicted values of TAN for fish ponds with different stocking densities.

& Longmore 2001; Burford & Lorenzen 2004) for shrimp culture practice. The present study shows the efficacy of these techniques for IMC culture fish ponds also.

In the present study, a user-friendly spreadsheet model has been developed based on an existing model (Burford & Lorenzen 2004) for prediction of TAN in IMC culture fish ponds. The results obtained in the present study showed the efficacy of the model. The developed user-friendly spreadsheet model can be used directly for prediction of TAN in IMC fish ponds cultured at any stocking density. This prediction of TAN in the fish ponds will help the users to adopt suitable measures in maintaining water quality in the fish ponds for successful fish production. For culture of other aquatic species, calibration, as well as validation, of the model parameters should be performed in the spreadsheet form before it is used for evaluation.

CONCLUSION

A spreadsheet model has been developed to predict the harmful nitrogenous compounds in intensive IMC cultured fish pond. The user-friendly format makes it convenient for the users to use the model to predict the concentrations of water quality parameters in culture media enabling the farmers to go for timely adoption of management practices which are otherwise difficult to decide. This is essentially helpful for farmers and entrepreneurs who do not have access to daily water quality measurement facilities. Once the model is calibrated and validated for a particular culture pond, it serves as a useful predictive tool in deciding the water quality management practices, like water exchange or sludge removal, to be adopted when the concentrations of parameters reach their permissible limits.

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