Aquaculture Pond Modeling for the Analysis of Integrated Aquaculture/Agriculture Systems: Fishpond Organic Matter and Nitrogen Dynamics

Interim Work Plan, DAST Study 5

Daniel M. Jamu and Raul H. Piedrahita
Biological and Agricultural Engineering Department
University of California
Davis, USA

Introduction

The development of models which allow for accurate simulation of organic matter, nitrogen, and fish production in ponds is important for analyzing the integration of aquaculture and agricultural systems. While various fishpond ecosystem models exist, they do not specifically include organic matter dynamics as primary components of the system. However, a majority of processes occurring in the water column and sediments of fishponds are related to the transformations of organic matter.

Current methods used to simulate organic matter dynamics and fish growth may be inadequate for models that specifically include organic matter processes in fish ponds (Jamu and Piedrahita, 1995; Munsiri and Boyd, 1995). Preliminary results reported by Jamu and Piedrahita (1995) showed that fish growth models need to be modified to include the effects of feed quality and differences in feed digestibility if the models are to accurately simulate organic matter transformations in fish ponds. This is especially true for pond management systems that utilize non-conventional feed and fertilizer sources. Munsiri and Boyd (1995) showed that, with the use of a single first-order rate constant to model organic matter degradation, equilibrium conditions were reached in a relatively short time, and organic matter accumulation rates were overestimated. The inadequacy of such an approach has also been recognized in marine sediment models. For example, Jorgensen (1979) recommended that organic matter be divided into different groups of compounds of different reactivity, each undergoing first-order decomposition. This report describes the modifications made to the modeling of organic matter dynamics in fishponds and presents preliminary results for fish growth rates, nitrogen, and organic matter accumulation obtained by the modified models.

Model Structure

The organic matter and nitrogen processes are components of the water quality and sediment submodels of the integrated aquaculture-agriculture model whose general framework was reported by Jamu and Piedrahita (1995). Details of each of the two sets of processes are described below.

Organic Matter Degradation

The simulation of organic matter degradation and accumulation rates is based on the multi-G model of Westrich and Berner (1984) which, after considering effect of temperature and media C/N ratio on the decomposition rate constant, can be expressed as:

$$\frac{dG_i}{dt} = -k_i \cdot G_i \cdot M_{CN} \cdot \tau \qquad (1)$$

$$-\frac{dG_{tm}}{dt} = \sum_{i=1}^{n} k_i \cdot G_i \cdot M_{CN} \cdot \tau \qquad (2)$$

$$G_{tm} = \sum_{i=1}^{n} G_i \qquad (3)$$

where,

- G_i = concentration of organic matter in each organic matter group (kg ha^{-1});
- G_{tm} = the total concentration of organic matter (kg ha^{-1});
- t = time (d);
- k_i = decay rate constant of each organic matter group (d^{-1});
- t = temperature parameter (0 to 1); and
- M_{CN} = carbon to nitrogen ratio parameter for organic matter group (0 to 1).

In this model, organic matter is grouped under three categories: (a) stable organic matter, (b) moderately decomposable organic matter, and (c) easily decomposable organic matter. Stable organic matter is defined as the organic matter which has undergone decomposition at least once (van Keulen and Seligman, 1987). The easily decomposable organic matter is made up of readily metabolizable subgroups of organic matter. In the current model, this group consists of carbohydrates and proteins. The moderately decomposable organic matter subgroup is made up of cellulose and lignin. These subgroups and stable organic matter are then used in the implementation of the model, and each has its own decay rate constant depending on its reactivity. The reactivities of the three subgroups and of stable organic matter are shown below in decreasing order. The values indicated in parenthesis are typical rates reported for the various groups (van Keulen and Seligman, 1987):

carbohydrates and proteins (0.8 d^{-1})
>> cellulose (0.05 d^{-1})
>> lignin (0.0095 d^{-1})
>> stable organic matter (8.3 x 10^{-5} d^{-1}) (4)

This decreasing reactivity order is reflected in decreasing values for the decay rate constants for the various organic matter groups. Mass balance calculations can be carried out for each of the organic matter groups using the corresponding decay rate coefficients and information on the composition of various organic matter sources in a pond (Figure 1). The concentrations of different groups or fractions of organic matter are determined from proximate analyses for different food or fertilizer types being applied to a fishpond. Proximate analyses and decay rate coefficients for different feed and fertilizer types are available from the literature (e.g. Gohl, 1981). The modified fish growth simulation model has been reported previously (Figure 1) (Jamu and Piedrahita, 1995).

While the simulation of organic matter transformations in the water column is relatively straightforward, the sediment component is complicated because of the existence of aerobic and anaerobic layers. For simplicity, the model has been designed to recognize two sediment layers only. First there is an upper 1-mm layer (Blackburn, 1990), with a dynamic oxygen concentration based on the oxygen concentration existing in the overlaying water; the second layer is the sediment beyond the first millimeter, which is considered to be anaerobic and homogenous with respect to sediment porosity and organic matter distribution. Whereas it is recognized that sediments will in fact be stratified within the anaerobic layer, this simplifying assumption is considered necessary at this point, given the information available on pond sediments and the relative biochemical activity at various depths.

$$\text{Diffusion rate} = (\text{Porosity}) \cdot (\text{Diffusion coefficient}) \cdot \frac{(\text{Concentration difference})}{\text{Depth}}$$

where,

Diffusion rate = diffusion rate for nitrogen species (kg $m^{-2}d^{-1}$);

Porosity = void volume fraction (dimensionless);

Diffusion coefficient = diffusion coefficient (m^2 d^{-1});

Concentration difference = difference in concentration between water and sediments (kg m^{-3}); and

Depth = sediment depth (m) (5)

Nitrogen Transformations

Nitrogen transformations for each organic matter group are simulated using first order models adopted in other fishpond ecosystem models (Piedrahita, 1990; Kochba et al., 1994). In addition, the nitrogen model includes a diffusion term for nitrate-nitrogen (NO_3^--N) and total ammonia nitrogen (TAN) between the water column and sediment. The diffusion of TAN and NO_3^--N is obtained from (Blackburn and Blackburn, 1992) (see above).

The sediment nitrogen component also includes adsorption of TAN by the sediments. The amount of TAN adsorbed is determined by a potential upper limit for TAN adsorption calculated from sediment cation exchange capacity (CEC) values (Mehrani and Tanji, 1974). The potential upper limit for TAN adsorption calculated from CEC values is only approximate, since not all exchange sites in the sediment are occupied by TAN as other cations compete for the exchange sites. In the model it is

Figure 1.

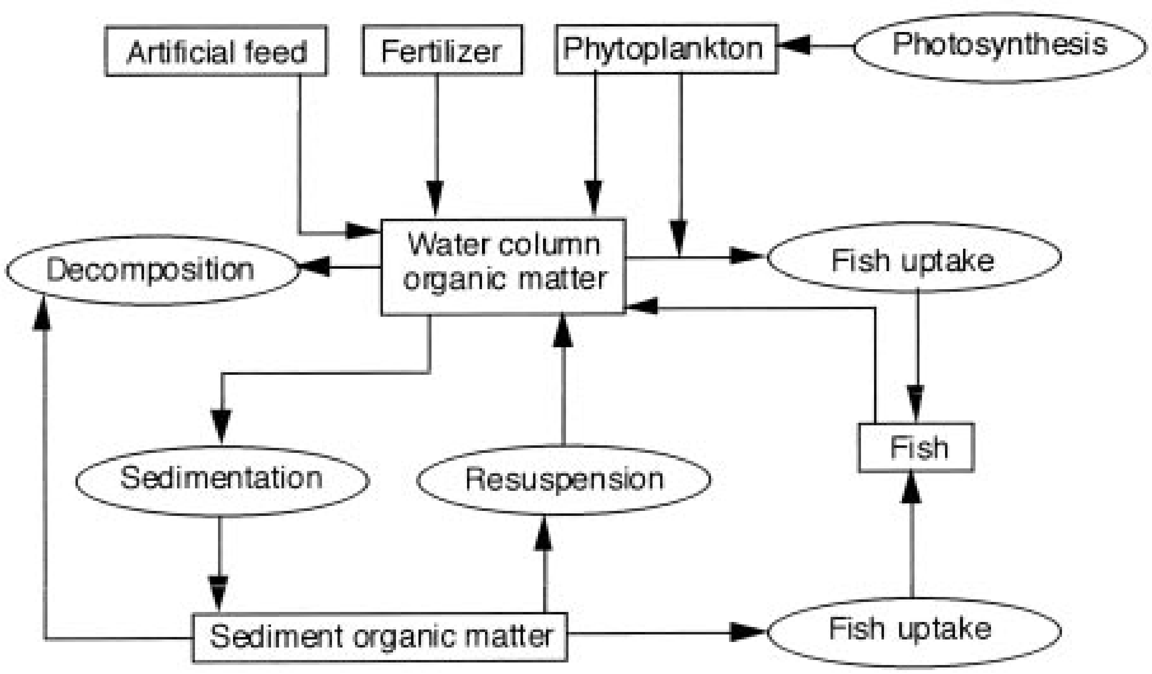

Figure 1. Schematic diagram of the sources and sinks for organic matter in the water column and in the sediment of an aquaculture pond.

$$\text{TANadsorption} = (\text{PorewaterTAN}) \cdot (\text{SpecificTANadsorption}) \cdot (\text{AdsorbedTAN})$$

where,

TANadsorption = Rate of TAN adsorption by the sediments (kg TAN ha-1 d-1)

PorewaterTAN = TAN in the pore water (kg ha-1)

SpecificTANadsorption = Specific rate of TAN adsorption (d-1)

AdsorbedTAN = Fraction of TAN adsorbed (Dimensionless) (6)

assumed that TAN adsorption will only occur when the potential upper limit for TAN adsorption is greater than the TAN adsorbed by the sediment; i.e., when the exchange sites are not completely occupied by TAN. The TAN adsorption rate is defined as the rate at which pore water TAN is attracted to the sediment through physical and chemical processes as well as mass action (Tchobanoglous and Schroeder, 1987). TAN adsorption rate can be obtained from the above equation (Deizman and Mostaghimi, 1991).

Other processes, sources, and sinks that are considered in nitrogen mass balance calculations are shown in Figure 2.

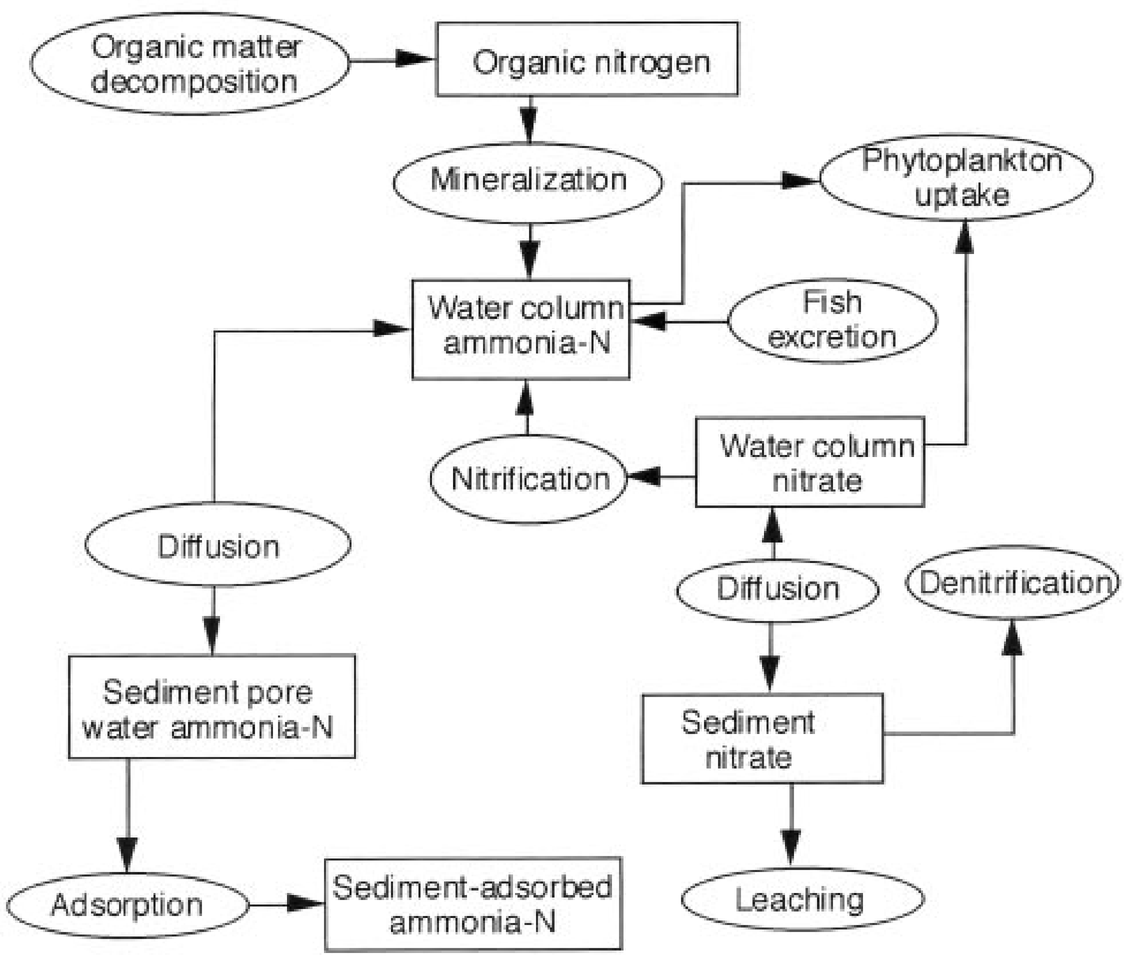

Figure 2. Schematic diagram of the sources and sinks for nitrogen in the water column and in the sediment of an aquaculture pond.

Results and Discussion

The model was run for a period of 145 days using parameter values and constants obtained from the literature. Environmental data and initial conditions for state variables were obtained from data corresponding to the PD/A CRSP Workplan 3 for the Butare, Rwanda site. The values simulated for fish growth, water column nitrate, and sediment nitrogen by the model were compared to observed data for the Rwanda site.

Fish Growth

The simulation of fish growth using a bioenergetic model modified to include the effect of feed quality and different digestibility coefficients for various feed types is shown in Figure 3. The fish growth rate simulated by the modified equation is similar to observed data at the site selected. The modified fish growth model takes into consideration the feed quality and feed digestibility coefficients of artificial feed. The model results are very promising so far, and after further development and testing, the model is expected to be a useful tool in the study of aquaculture systems models where agricultural wastes are the primary feed input sources.

Organic Matter and Nitrogen Dynamics

Simulation results for water column and sediment organic matter using the multi-G model for organic matter degradation are shown in Figure 4 for the same data set used for the fish growth trials. The Rwanda data do not include sediment organic matter production, hence model output cannot be compared to data from this site. However, the final sediment organic matter concentration of 2,620 kg ha^{-1} is similar to values reported for agriculture waste-fed ponds (2,000-2,100 kg ha^{-1}) (Hiwagara and Mitsch, 1994; Jamu, unpublished data). The results for final water column organic matter concentrations (650 kg ha^{-1}) also fall within the range (140-770 kg ha^{-1}) reported for agricultural waste-fed ponds (ICLARM-BMZ/GTZ, in press; Milstein et al., 1995).

Water column nitrate follows a trend similar to the observed data (Figure 5), but the simulation of other nitrogen parameters need further development. The preliminary results for sediment nitrogen show that the concentration of soil nitrogen (0.14 kg nitrogen/kg sediment organic matter dry weight) obtained in the simulations is much higher than the value observed (0.27 mg nitrogen/kg soil).

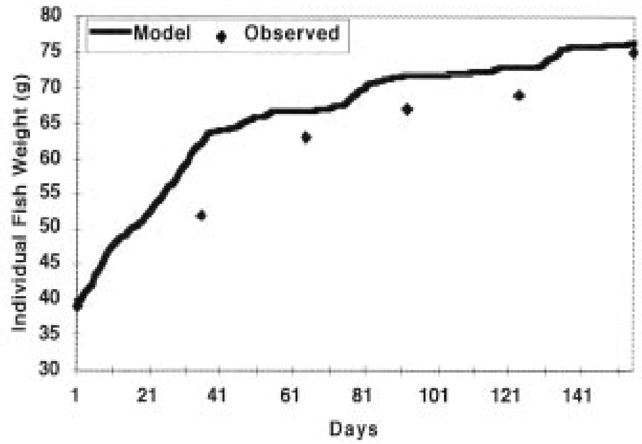

Figure 3. Fish weight predicted by the modified bioenergetics model for the Butare site in Rwanda.

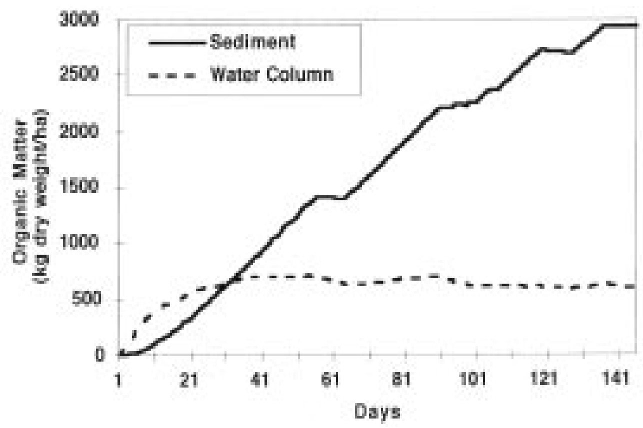

Figure 4. Water column and sediment organic matter predicted using the multi-G organic matter model.

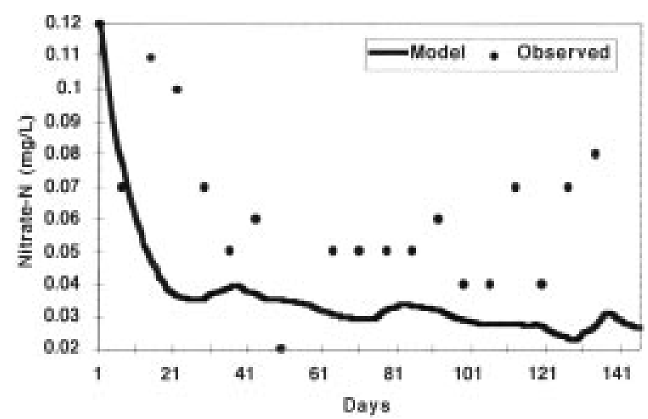

Figure 5. Water column nitrate nitrogen simulation for the Butare site in Rwanda.

However, the model sediment nitrogen concentration is based on sediment organic matter only. The average organic matter content for pond soils is 4% (Boyd, 1995), and simulated soil nitrogen values are approximately two orders of magnitude greater than expected. Other nitrogen processes (e.g., diffusion and TAN adsorption) in the sediment are directly linked to the amount and depth of sediments. Information on the extent to which the native pond soil participates in nitrogen processes should improve the simulation of sediment nitrogen processes.

Literature Cited

Blackburn, T.H., 1990. Denitrification model for marine sediments. In: Sorensen, J., and N.P. Revsbech (Editors). Denitrification in Soil and Sediment. Plenum Press, New York, pp. 323-337.

Blackburn, T.H. and N.D. Blackburn, 1992. Model of nitrification and denitrification in marine sediments. FEMS Microbiology Letters, 100:517-522.

Boyd, C.E., 1995. Bottom Soils, Sediment, and Pond Aquaculture. Chapman and Hall, New York, 348 pp.

Deizman, M.M. and S. Mostaghimi, 1991. A model for evaluating the impacts of land application of organic waste on runoff water quality. Research Journal WPFC, 63:17-27.

Gohl, B., 1981. Tropical Feeds: Feed Information Summaries and Nutritive Values. FAO, Rome, 529 pp.

Hiwagara, H. and W.J. Mitsch, 1994. Ecosystem modeling of a multi-species integrated aquaculture pond. Ecological Modeling, 72:41-73.

ICLARM-BMZ/GTZ, in press. The ICLARM-BMZ/GTZ Africa Aquaculture Project: Final Technical Report. International Center for Living Aquatic Resources-Bundesministerium für wirtschaftliche Zusammenarbeit/Deutsche Gesselleschaft für Technische Zusammenarbeit.

Jamu, D.M. and R.H. Piedrahita, 1995. Aquaculture pond modeling for the analysis of integrated aquaculture/agriculture systems. In: H. Egna, B. Goetze, D. Burke, M. McNamara, and D. Clair (Editors), Thirteenth Annual Technical Report, Pond Dynamics/Aquaculture CRSP, Office of International Research and Development, Oregon State University, Corvallis, Oregon, USA, pp. 142-147.

Jorgensen, B.B., 1979. A comparison of methods for the quantification of bacterial sulfate reduction in coastal marine sediments. II. Calculation from mathematical models. Geomicrobiol. J., 1:29-47.

Kochba, M., S. Diab, and Y. Avnimelech, 1994. Modeling nitrogen transformations in intensively aerated fish ponds. Aquaculture, 120:95-104.

Mehrani, M. and K.K. Tanji, 1974. Computer modeling of nitrogen transformations in soils. J. Environ. Quality, 3:391-396.

Milstein, A., A. Akron, I. Karpus, M. Kochba, and Y. Avnimelech, 1995. Combined effects of fertilization rate, manuring, and feed pellet application on fish performance and water quality in polyculture ponds. Aquaculture Research, 26:55-65.

Munsiri, P. and C.E. Boyd, 1995. Physical and chemical characteristics of bottom soil profiles in ponds at Auburn, Alabama, USA, and a proposed system for describing pond soil horizons. World Aquaculture Society, 26:346-377.

Piedrahita, R.H, 1990. Calibration and validation of TAP, an aquaculture pond water quality model. Aquacultural Engineering, 9:75-96.

Tchobanoglous, G. and E.D. Schroeder, 1987. Water Quality. Addison and Wesley, Massachusetts, 768 pp.

van Keulen, H. and N.G. Seligman, 1987. Simulation of water use, nitrogen nutrition and growth of spring wheat. Pudoc, Wageningen, 310 pp.

Westrich, J.T. and R.A. Berner, 1984. The role of sedimentary organic matter in bacterial sulfate reduction: The G-model tested. Limnol. Oceanogr., 29:236-249.