

**AQUACULTURE POND MODELING FOR THE ANALYSIS OF ENVIRONMENTAL
IMPACTS AND INTEGRATION WITH AGRICULTURE: MODELING OF TEMPERATURE,
DISSOLVED OXYGEN, AND FISH GROWTH RATE IN STRATIFIED PONDS USING
STOCHASTIC INPUT VARIABLES**

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INTRODUCTION

The prediction of water temperature and dissolved oxygen (DO) in stratified fish ponds can help in managing water quality and improving fish production. A model is being developed to simulate water temperature, DO, and fish growth under the effects of random weather variables. Values for solar radiation, air temperature, and wind speed are generated using stochastic methods. The water column is considered to be uniform in the horizontal plane but not in the vertical, where three distinct layers are considered: surface, mid-depth, and bottom. Diurnal water temperature, DO, and other related water quality and biological variables are simulated for these three water layers.

The model consists of several inter-related components: the generation of values for weather parameters and the simulation of water temperature, DO concentration, and fish weight. The weather values are generated using stochastic methods based on statistical analysis of the local weather data. The water temperature and DO models have been constructed based on an initial deterministic model for simulating water temperature and DO over periods of approximately 24 hours (Losordo, 1988; Culberson, 1993). The fish growth rate simulation is adapted from the model developed by Bolte et al. (1995) and modified by Jamu and Piedrahita (1997).

Modifications and development of the model during the reporting period have been concentrated in the following areas:

1. Improvement of the way in which phytoplankton respiration is quantified;
2. Modification of the model so that pond water exchanges can be considered;
3. Consideration of different types of organic matter with varying rates of decomposition and oxygen consumption; and
4. Modification of the fish growth model to allow for the consumption of different types of foods.

Developments in each of these areas are described below.

Phytoplankton Respiration

Phytoplankton dynamics tend to dominate the oxygen cycle in most aquaculture ponds. Accurate prediction of the rates of phytoplankton growth and respiration is essential in obtaining water quality simulations that closely match the reality of aquaculture pond behavior. The rates of oxygen production and consumption by phytoplankton vary as functions of environmental conditions and other parameters. The phytoplankton primary production rate takes into account the effects of light intensity, ammonia nitrogen concentration (as a source of inorganic nitrogen), water temperature, and the concentration of chlorophyll *a*. Phytoplankton "consumption" terms, other than the phytoplankton respiration term, in the mass balance calculations are: phytoplankton death, grazing by fish, and sinking or settling of phytoplankton to the sediment. These consumption terms are modeled using a first order model with constant specific rates. However, in the current model, the concentration of DO and water temperature have been included

in the equations used to simulate the phytoplankton respiration rate:

$$K_{chla} = k_{sp} f(t) \frac{C}{k_c + C} \quad (1)$$

where

- K_{chla} = phytoplankton respiration rate (1/h),
- k_{sp} = specific reference phytoplankton respiration rate at 20°C (1/h),
- $f(t) = \theta^{(T-20)}$ temperature dependence (unitless),
- C = oxygen concentration, (mg l⁻¹),
- k_c = half saturation constant of oxygen respiration (mg l⁻¹).

Pond Water Exchange

In most PD/A CRSP fish ponds, water is added to maintain the water level and to make up for losses due to evaporation and infiltration, but there is no effluent during normal pond operation. However, water exchange in fish ponds may have a significant impact on water quality. Similarly, the effluent from fish ponds may introduce significant amounts of nutrients into receiving waters. The model under development was modified to include water inflow and outflow terms in the energy and mass balance calculations for temperature and water quality, respectively. The modifications make it possible to use the model to estimate water quality changes in a pond caused by water exchange and to quantify the quality of the effluent and possible nutrient releases to the environment.

In the current version of the model two assumptions are made regarding water exchange. The first assumption is that the water influent and effluent flow into and out of the pond surface layer. The second assumption is that the water inflow is well mixed with pond water in the surface layer, and that there are no temperature and DO differences within that layer. The equations for the energy balance and DO mass balance are presented in a simplified form to illustrate the inclusion of the influent and effluent terms. The energy change due to the water inflow and outflow is expressed as:

$$\frac{dH_E}{dt} = H_{in} - H_{out} \quad (2)$$

$$H_{in} = Q_{in} C_p \rho T_{in} \quad (3)$$

$$H_{out} = Q_{out} C_p \rho T_{out} \quad (4)$$

where

- $\frac{dH_E}{dt}$ = rate of heat flux due to water exchange through the pond (kJ h⁻¹),
- Q_{in} = rate of water inflow (m³ h⁻¹),
- C_p = water heat capacity, (kJ kg⁻¹ °C⁻¹),
- ρ = water density (kg m⁻³),
- T_{in} = temperature of the influent water (°C),
- Q_{out} = rate of water outflow (m³ h⁻¹),
- T_{out} = temperature of the effluent water (°C).

The DO change caused by the water exchange can also be presented in a simplified form:

$$\frac{dC_E}{dt} = DO_{in} - DO_{out} \quad (5)$$

$$DO_{in} = Q_{in} C_{in} \quad (6)$$

$$DO_{out} = Q_{out} C \quad (7)$$

where

- $\frac{dC_E}{dt}$ = DO rate of change caused by the water exchange (g h⁻¹),
- C_{in} = oxygen concentration in the inflow (g m⁻³),
- C = oxygen concentration in the fish pond (g m⁻³).

Equations (2) and (5) may be applied to a different water layer (middle or bottom layers) if the location of the influent or effluent is such that water is being added or removed from those layers. Although heat capacity is a function of temperature, it is assumed to be the same for the influent and effluent because the heat capacity difference between the two waters is negligible compared to other changes and processes in the pond.

Organic Matter Decomposition

Fish ponds may receive various organic and inorganic fertilizers and feeds. The types, amounts, and application methods of organic fertilizers and feeds affect the concentrations of DO significantly according to the decomposition rate of organic matter introduced. In the previous version of this model (Lu and Piedrahita, 1997), oxygen consumption in the water column due to organic matter decomposition was assumed to be a function of water temperature only. This approach did not consider the changes of the concentrations of various forms of organic matter, such as fertilizers, dead phytoplankton, uneaten fish feed, etc. Although the oxygen consumption due to nitrification was separated from the water column respiration, and ammonia concentration is simulated using mass balances, the ammonia nitrogen reduction via the decomposition of organic nitrogen could not be predicted accurately due to the non-inclusion of the dynamics of organic matter in the model.

In the past, fish ponds at the PD/A CRSP research sites have been fertilized with different types of fertilizers, and the model has been modified such that fertilizer differences can be taken into account. The model to simulate organic matter decomposition has been adapted from that developed by Jamu and Piedrahita (1997). Three types of organic matter components are considered based on their decay rate: easily decomposed material with a high rate of decomposition, material with a moderate rate of decomposition, and stable organic matter having a low decomposition rate. In this model only two decomposition rates are included since the stable material is considered to create a negligible oxygen demand. The two types of organic material considered are:

1. The easily decomposed organic matter, such as carbohydrate and proteins; and
2. Organic matter with a moderate rate of decomposition, such as cellulose and lignin.

The average decomposition rate of a given material can be estimated based on its approximate composition and concentration of carbohydrates and crude protein (easily biodegradable), and cellulose and lignin (moderately biodegradable). The organic matter included in the current model comprises fertilizers, fish fecal material, and dead phytoplankton. The concentration for each type of

organic matter is simulated using mass balance equations.

Uptake of Various Feed Types

Most PD/A CRSP experiments have not used artificial food in the past; however, this trend is changing in current and future experiments. The change is in part a result of shifts in how pond aquaculture is viewed and carried out throughout the world. As a result, the pond model has been modified such that artificial food and various natural feed sources can be considered. The model for the simulation of multiple feed uptake has been adapted from the model developed by Jamu and Piedrahita (1996), which was in turn based on the work of Bolte et al. (1995). Feed uptake is considered to be dependent on the concentration of the various feed sources and on the preference of fish for a particular feed type. The assumption made is that fish take the preferred feed until it can not meet their intake demand, at which point a substitute feed will be taken. In the current model, the artificial feed is the preferred feed and is consumed by the fish whenever it is available. Other possible food sources considered in the model are phytoplankton and detritus or particulate organic matter.

Simulation Results

The model was tested using data from the PD/A CRSP Rwanda site. The model was run 20 times for a simulation period of 146 days. The hourly solar radiation, air temperature, and wind speed were generated based on the statistics of the 1986 to 1991 data from the Rwanda site. The input variables used were from ponds CO5, DO6, and DO8, Work Plan 4, Experiment 3. The ponds were fertilized using chicken manure, green grass, and urea.

The average, maximum, and minimum values of water temperature and DO at the three pond depths after 20 model runs are listed in Table 1. The simulated values indicate a high degree of stratification, which is probably caused by the high light extinction coefficient and high phytoplankton concentration. The frequency distributions of DO for the surface, middle and bottom layers are shown in Table 2. The simulated chlorophyll *a* values are compared to the measured data in Figure 1. There are few measurements of chlorophyll available in the data set, and there is very high variability in the data. For example, three ponds (CO1, DO6, and DO8) undergoing the same

Table 1. Simulated temperature and DO for surface, middle, and bottom layers. The values represent means of hourly values obtained for the 146-day simulations.

Variables	Average	Minimum	Maximum
TEMPERATURE (°C)			
Surface	16.77(1.25)	13.49(0.96)	24.00(2.35)
Middle	19.33(0.59)	16.62(0.87)	18.67(0.50)
Bottom	18.67(0.50)	16.32(0.80)	20.87(0.65)
DO (mg l ⁻¹)			
Surface	3.65(2.96)	0.27(0.64)	9.99(7.42)
Middle	1.06(1.0)	0.07(0.41)	3.19(2.34)
Bottom	0.2(0.44)	0.02(0.37)	0.94(1.12)

Standard deviations in parentheses.

Table 2. Percent frequency distribution of DO for surface, middle, and bottom layers. The numbers indicate the fraction of the total number of hours simulated during which the DO was within the ranges indicated.

DO (mg l ⁻¹)	Surface	Middle	Bottom
0-1	12.99	23.29	68.29
1-2	21.03	42.24	26.28
2-3	11.13	15.04	4.37
3-4	9.79	10.30	0.71
4-5	7.65	4.51	0.09
5-6	5.54	1.94	0.03
6-7	4.42	1.28	0.03
7-8	4.54	0.57	0.03
8-9	4.08	0.49	0.17
9-10	3.42	0.11	0.00
10-11	2.45	0.06	0.00
> 11	12.96	0.17	0.00
Total	100.00	100.00	100.00

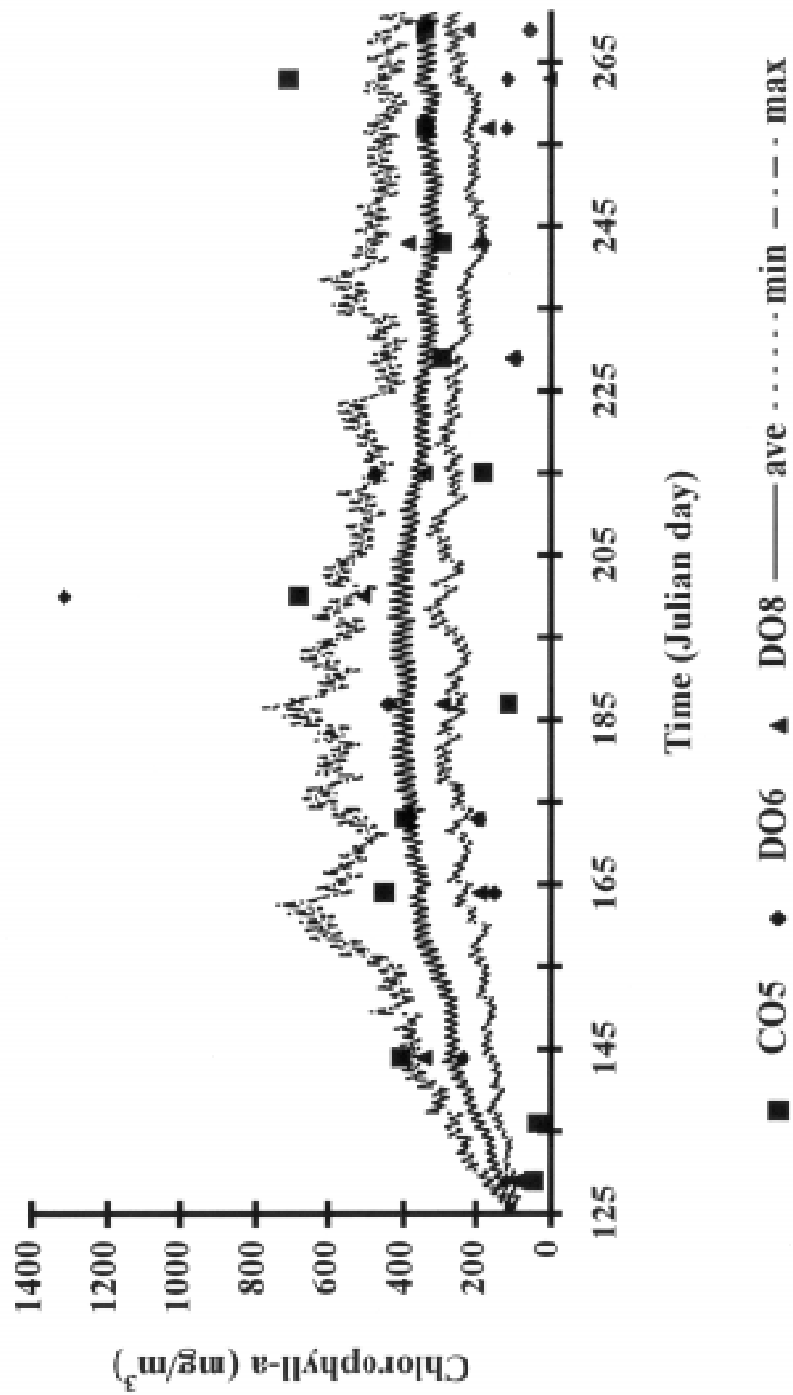


Figure 1. Simulated and measured chlorophyll *a* values for three replicate ponds (CO5, DO6, and DO8).

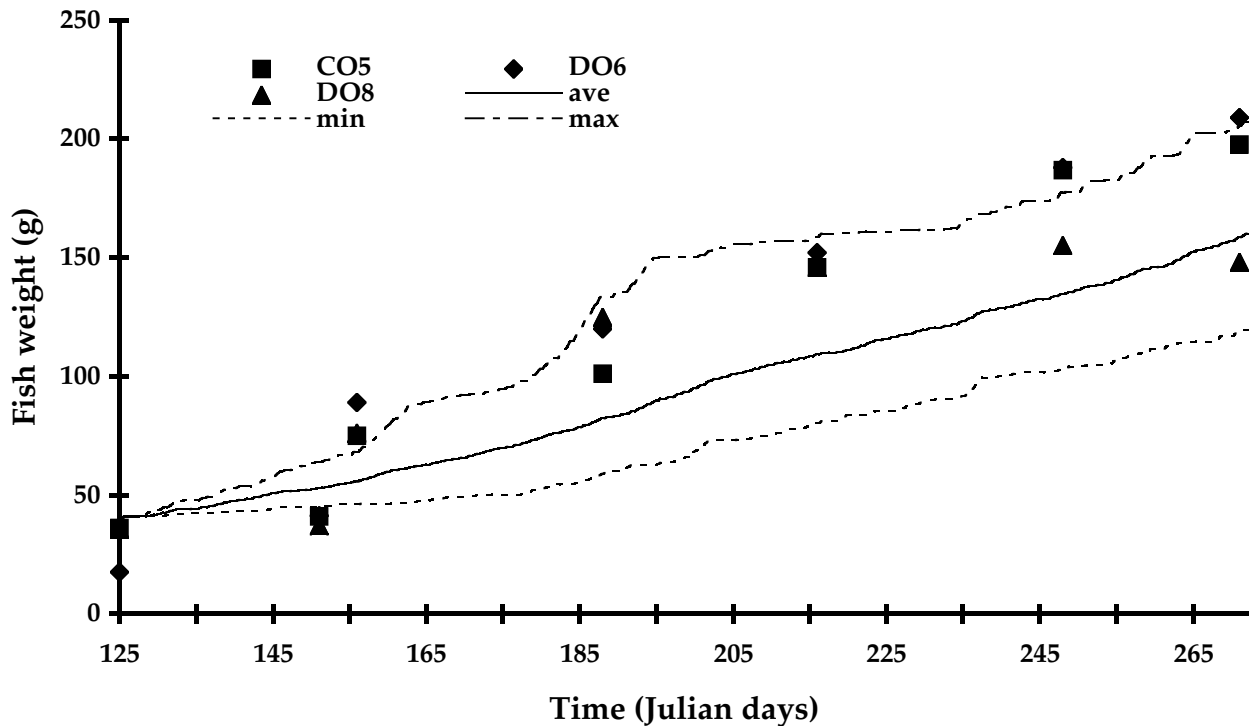


Figure 2. Simulated and measured average fish weights for three replicate ponds (CO5, DO6, and DO8).

treatment had chlorophyll *a* concentrations of 709, 114, and 0 mg m⁻³, respectively. Figure 2 shows a comparison of the simulated average individual fish weight with the measured data indicating good agreement between the model and the data. Figure 2 also illustrates the widening of the probable range of expected fish sizes as the duration of the grow-out period is increased.

ANTICIPATED BENEFITS

The model facilitates the prediction of ranges of water temperature, dissolved oxygen, and fish growth rate under different treatments (feeding and fertilization regimes). The simulation results will be useful for fish pond site selection and management.

FUTURE DIRECTIONS

Improvements to the model are still needed in the following areas: the ammonia concentration effects on phytoplankton growth, and fish mortality rate due to the variability of the water quality. The model will be calibrated and validated using PD/A CRSP data from different treatments and/or sites.

LITERATURE CITED

- Bolte, J.P., S.S. Nath, and D.E. Ernst, 1994. POND®: A decision support system for pond aquaculture. In: H. Egna, J. Bowman, B. Goetze, and N. Weidner (Editors), Twelfth Annual Technical Report. Pond Dynamics/Aquaculture CRSP, Office of International Research and Development, Oregon State University, Corvallis, Oregon, pp. 48-67.
- Culberson, S.D., 1993. Simplified model for prediction of temperature and dissolved oxygen in aquaculture ponds: using reduced data inputs. M.S. thesis, University of California, Davis, 212 pp.
- Jamu, D.M. and R.H. Piedrahita, 1996. 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, pp. 172-177.