Dissolved Oxygen Stratification Modelling of Small Shallow Aquaculture Ponds

Jiacai Gao
Manly Hydraulics Laboratory, Department of Public Works and Services, 110B King Street, Manly Vale, NSW 2093

Noel P Merrick
National Centre for Groundwater Management, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007

Abstract A mathematical model has been developed to simulate temporal variations and vertical stratification of dissolved oxygen (DO) in aquaculture ponds. The model is coupled with a temperature stratification model. Along with chlorophyll *a* (Chl *a*) and biochemical oxygen demand (BOD) sub-models, the DO sub-model has been formulated to include photosynthesis, respiration, surface reaeration, oxidation of BOD, sediment oxygen demand (SOD), nitrification oxygen loss and prawn (or fish) oxygen consumption as source and sink terms. The model uses a fully implicit central difference scheme to discretise the partial differential equation for a control volume. The time step of one hour and distance step of 2 cm are sufficient to obtain accurate results. The model runs for 24 hours. Measured DO profiles from both freshwater and salt-water ponds were used to calibrate and validate the developed model. The average regression coefficients for model calibration and validation are 0.85 and 0.73, respectively, and the maximum simulation errors are less than 4 mg/L (with one exception). The exception is a pond with weak DO stratification, where the model performs poorly. The model predicts DO stratification events within 1-3 hours, and predicts the range of the maximum DO stratification reasonably well. The model generally performs better near the water surface and middle depths than at the pond bottom. Sensitivity analyses show that the model is very sensitive to chl *a* related coefficients and physical processes. The model is also sensitive to SOD. The model is very sensitive to whether chl *a* is simulated or not. The model is not sensitive to BOD related processes or prawn related coefficients.

1. INTRODUCTION

Dissolved oxygen (DO) is one of the most important water quality parameters in aquaculture ponds. There is a number of documented DO models of aquaculture ponds [Busch et al., 1977; Romaire et al., 1978; Cassinelli et al., 1978; Meyer, 1980; Meyer and Brune, 1982; Madenjian et al., 1987a,b; Smith and Piedrahita, 1988; Losordo, 1988; Chang and Ouyang, 1988 and Gao ,1997]. Almost all the models assume a uniform pond condition. The magnitude of DO stratification noted by Losordo [1988], Chang and Ouyang [1988] and Gao [1997], suggests that this effect must be explicitly accounted for to obtain accurate prediction of temperature and DO concentration. Simulations with fully mixed models do not provide accurate predictions of the dissolved oxygen concentration to which the animals are exposed. The only documented DO stratification models are those of Losordo [1988] , Chang and Ouyang [1988] and Gao [1997].

Dissolved oxygen fluctuation is largely controlled by the algae photosynthesis and respiration. Algal biomass concentration can be expressed in a number of different ways including dry weight of algae, carbon content, and chlorophyll *a* concentration. Because the purpose of the model is to determine productivity rather than actual biomass, the concentration of chlorophyll *a* in a water volume is used to represent an algal population.

This paper describes the development and application of an aquaculture pond DO model along with chlorophyll *a* and BOD models. The model calibration and validation against measured DO profiles are discussed.

2. MODEL DEVELOPMENT

2.1 Algae Transport Equation

Fluctuations of chlorophyll *a* concentration in a volume of water are due to the combined effects of growth, respiration, mortality, diffusion, and settling. A general form of the unsteady, one-dimensional algae transport equation is given by [Riley, 1988; Riley and Stefan, 1988; Gao, 1997]:

$$\frac{\partial Chla}{\partial t}+\frac{V_c}{A}\frac{\partial(AChla)}{\partial z}-\frac{1}{A}\frac{\partial}{\partial z}(AK\frac{\partial Chla}{\partial z})+k_m\theta_m^{T-20}Chla+k_r\theta_r^{T-20}Chla$$

$$-\mu_{max}f(T)\min[f(L),f(P),f(N)]Chla=0$$

where Chl *a* is chlorophyll *a* concentration (mgL^{-1}), V_c is settling velocity of chlorophyll *a* (mh^{-1}), A is horizontal area (m^2), K is turbulent diffusion coefficient (m^2h^{-1}), μ_{max} is the maximum growth rate at a particular reference temperature under optimal conditions of saturated light intensity and excess nutrients (h^{-1}), f(T) is temperature function for algal growth, f(L), f(P), f(N) are growth limiting functions for light, phosphorus and nitrogen, respectively, k_r is respiration rate constant (h^{-1}), θ_r is temperature adjustment factor, T is water temperature (°C), k_m is mortality rate constant (h^{-1}), θ_m is temperature adjustment factor.

2.2 DO Transport Equation

Fluctuations of DO concentration in a pond are due to the combined effects of photosynthesis, respiration, surface reaeration, oxidation of BOD, sediment oxygen demand (SOD), nitrification oxygen loss and prawn (or fish) oxygen consumption. A general form of the unsteady, one-dimensional DO transport equation is given by [Riley and Stefan, 1988; Stefan and Fang, 1994; Gao, 1997]:

$$\frac{\partial DO}{\partial t} - \frac{1}{A}\frac{\partial}{\partial z}\left(AK\frac{\partial DO}{\partial z}\right) + \frac{1}{YCHO2}\left(k_r\theta_r^{T-20} - \mu_{max} f(T)\min[f(L), f(P), f(N)]\right)Chla$$

$$+ k_b\theta_b^{T-20}\frac{DO}{K_{BOD}+DO}BOD + \frac{1}{A}S_{b20}\theta_s^{T-20}\frac{DO}{K_{SOD}+DO}\frac{\partial A}{\partial z} + \frac{64}{12}k_{NIT}\theta_{NIT}^{T-20}\frac{DO}{K_{NIT}+DO}NH3$$

$$-\frac{K_L}{\Delta z_s}(DO_{sat} - DO)_{surface} + S_{AQUA} = 0$$

where DO is dissolved oxygen concentration (mgL^{-1}), YCHO2 is ratio of mg chlorophyll *a* per mg oxygen utilised and released in photosynthesis and respiration (mg chla $(mg\ O_2)^{-1}$), K_L is the surface oxygen transfer velocity ($m\ h^{-1}$), Δz_s is the thickness of the surface layer (m), DO_{sat} is saturated dissolved oxygen concentration in the first layer ($mg\ L^{-1}$), k_b is first order decay coefficient (h^{-1}), BOD is detritus as oxygen equivalents ($mg\ L^{-1}$), K_{BOD} is half saturation constant for oxygen limitation, S_{b20} is the SOD value at T=20 °C ($g\ O_2\ m^{-2}\ h^{-1}$), K_{SOD} is half saturation constant for SOD, k_{NIT} is nitrification rate at 20 °C (h^{-1}), K_{NIT} is half saturation constant for nitrification ($mg\ L^{-1}$), NH3 is ammonia nitrogen concentration ($mg\ L^{-1}$), θ_b, θ_s and θ_{NIT} are temperature adjustment coefficients. S_{AQUA} is given by Losordo [1988] and Gao [1997].

2.3 BOD Transport Equation

BOD concentration is also simulated in the model. The model formulation for BOD is relatively easy due to the simple kinetics involved. The fluctuation of BOD in a pond is controlled by algae death, BOD decay and its settling and diffusion. The transport equation for BOD is:

$$\frac{\partial BOD}{\partial t} + \frac{V_b}{A}\frac{\partial(ABOD)}{\partial z} - \frac{1}{A}\frac{\partial}{\partial z}\left(AK_z\frac{\partial BOD}{\partial z}\right)$$

$$-\frac{1}{YCBOD}k_m\theta_m^{T-20}Chla + k_b\theta_b^{T-20}BOD = 0$$

where YCBOD is ratio of mg chlorophyll *a* to mg oxygen utilised in organic decay(mg chla $(mg\ BOD)^{-1}$), V_b is settling velocity of BOD (mh^{-1}).

2.4 Numerical Scheme

A fully implicit central difference scheme is used to discretize the partial differential equations. The discretization of each equation yields a set of linear equations, one for each layer, which are solved simultaneously. A modified Gauss elimination procedure is used to solve the tri-diagonal matrix operating only on the three non-zero diagonal terms.

The model is applied in a time step of one hour. The DO simulation follows temperature, chlorophyll *a* and BOD calculations. There is not sufficient data to calibrate the algae alone. The field data of dissolved oxygen profiles with depth are used for calibration of the model coefficients.

3 RESULTS AND DISCUSSION

3.1 Model Calibration

The algae and DO model is calibrated after the calibration and validation of the temperature model [Merrick and Gao, 1997]. The algal respiration rate (k_r), mortality rate (k_m), algae settling velocity (V_{chla}), BOD decay rate (k_b), and BOD settling velocity (V_{BOD}) are calibration coefficients for the model. The maximum algal growth rate (μ_{max}), algal growth optimal temperature and light (T_{opt} and I_{opt}), initial chlorophyll *a* ($Chla_{init}$), initial BOD (BOD_{init}) concentration, and sediment oxygen demand coefficient (S_{b20}) are also calibration coefficients, but their adjustments are bound by the measured values. The calibration coefficients are adjusted to achieve optimal fit between simulated and measured dissolved oxygen profiles, and to give stable and logically reasonable results for chlorophyll *a*. A parameter estimation model, PEST [Doherty, 1994], is used in the model calibration.

Two ponds which were used for temperature model calibration are selected for model calibration. Five ponds are used for the model validation. The result of the algae and DO model calibration run of one of the calibration ponds is given in Figure 1. Also shown on Figure 1 are the simulated chlorophyll *a* and BOD contour lines.

The regression coefficient (R^2) is 0.91 and 0.78 for the two calibration runs, respectively. Generally, the simulations match the field data well. The maximum over- and under-estimation errors are 1.51, -1.54 and 3.79, -3.84 mg/L for the two calibration ponds, respectively.

The agreement of measured and simulated DO is generally good at all depths for the two calibration runs.

The results of the two calibration runs demonstrate that the algae and DO model can accurately predict whether DO in a pond will become stratified or not. In terms of simulating the timing of the onset of DO stratification, maximum DO stratification, and the iso-DO conditions, the resulting accuracy is good for the two runs. The simulation results predict the time of the actual stratification process events within three hours.

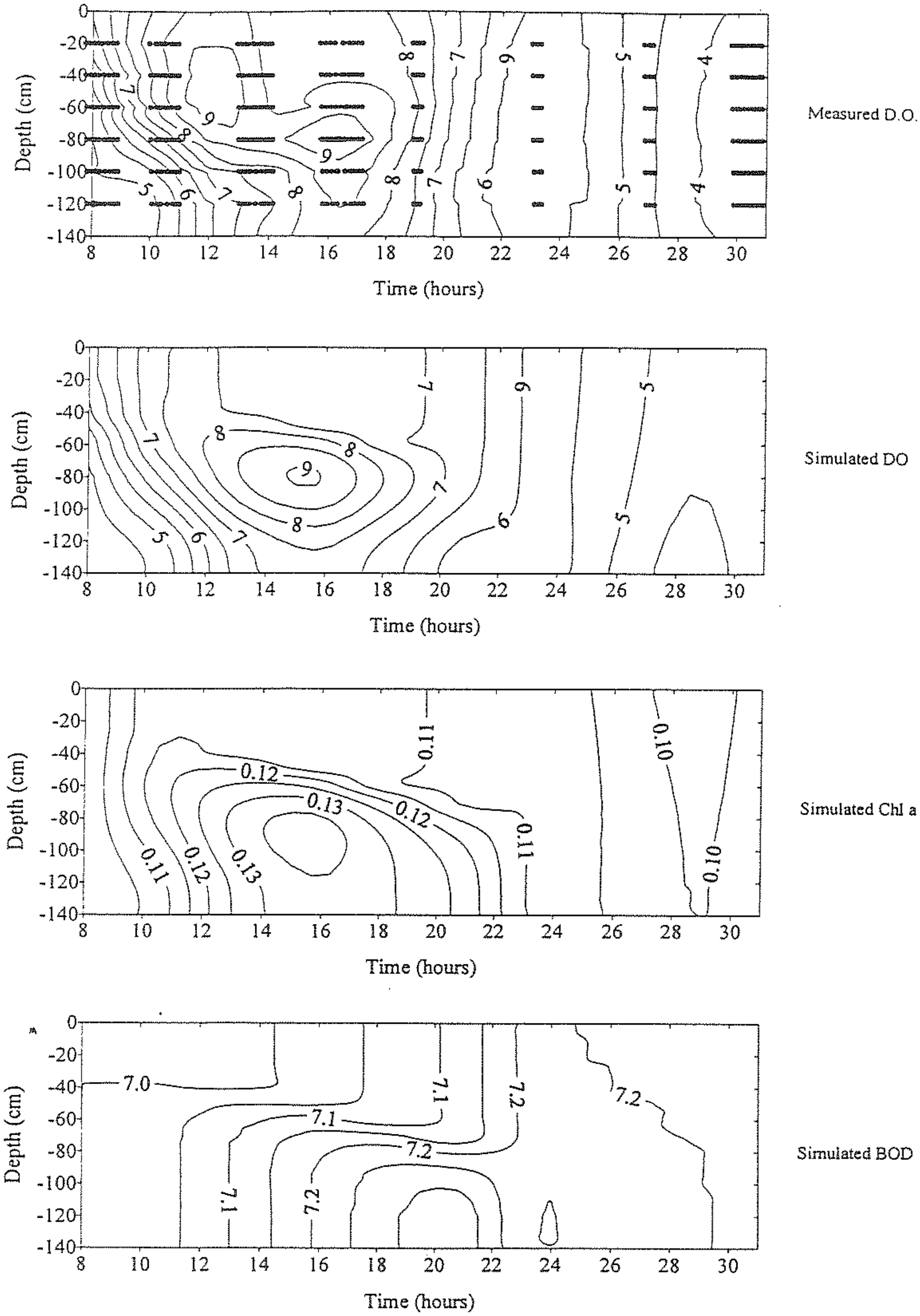

Figure 1 Measured and simulated DO contours and simulated chlorophyll *a* and BOD contours of one of the calibration ponds

The BOD variations (both spatial and temporal) are very small (within 5%) in both simulations. This is justified because there is no significant source or sink for BOD except chlorophyll *a* death and decay of BOD itself.

3.2 Sensitivity Analysis

The sensitivity analysis for coefficients in the algae and DO model is made for one of the calibration ponds (reference run). Only one coefficient at a time is changed from the reference value, other coefficients being kept at the reference values. The coefficients for the sensitivity analysis can be classified into six groups: algae process, BOD process, DO process, prawn related coefficients, physical process, and whether the chlorophyll *a* and/or BOD are simulated.

In general, the model is not sensitive to the BOD related process (k_b, V_{BOD} and BOD concentration) and prawn related coefficients (w_{prawn}, N_{prawn} and BL_{prawn}). The model is very sensitive to the chlorophyll *a* related coefficients (μ_{max}, k_r, I_{opt}, T_{opt}, $Chla_{init}$) and physical processes (W, PAR, HKmax, η_o). The model is also sensitive to the SOD. The model is very sensitive to whether the chlorophyll *a* is simulated or not. On the contrary, there is no effect on the DO structure whether BOD is simulated or not.

It is noted that varying coefficients more or less changes the magnitude of the maximum DO stratification. But in most cases, the timing of the maximum stratification remains the same.

In terms of sensitivity variations with depth, most of the coefficients tested have the same effects at all depths. The following coefficients have more effects at the pond bottom: extinction coefficient (η), light limitation coefficient (k_1), light inhibition coefficient (k_2), sediment oxygen demand (S_{b20}), and location of prawns (z_{prawn}). The only coefficient which has an effect on the surface DO profile is the DO transfer coefficient (K_L).

3.3 Model Validation

After literature review, calibration and sensitivity analysis, the coefficients are fixed in sets depending on the pond environmental conditions. There are no calibration parameters in the application of the model for validation purposes.

Five ponds are used for model validation. The regression coefficients (R^2) are larger than 0.75 for three of the validation ponds. Generally, the simulated DO matches the measurement data quite well. The regression coefficient is 0.56 for one of the validation ponds in which DO stratification is more than 20 mg/L in 1 meter depth. The regression coefficient is only 0.33 for another validation pond, an example of a poor match. The pond has a strong thermal stratification but has minor DO stratification only. Influenced by the calculated temperature stratification structure, simulated DO has distinct stratification, which causes the significant errors.

In the model validation runs, the algae and DO model performs better at water surface and middle depth than at the pond bottom. The model predicts stratification events within 1-3 hours of the actual events (with one exception for the pond which has no measured DO stratification less than 1 mg/L). The model also predicts the magnitude of the maximum stratification with maximum errors (under- and over-estimation) from -1.5 to 0.9 mg/L (except for one pond with an error of -4.9 mg/L).

4. CONCLUSIONS

A vertical one-dimensional dissolved oxygen model along with algae and BOD models has been formulated for aquaculture ponds in a wide range of environmental conditions. The DO model includes photosynthesis, surface reaeration, plant respiration, biochemical oxygen demand, sediment oxygen demand, nitrification oxygen loss and prawns (or fish) oxygen consumption as source and sink terms. The chlorophyll *a* and BOD are simulated before the DO concentration is computed.

The DO simulations match field data well. The DO model predicts time of DO stratification onset, maximum stratification and iso-DO conditions (within 1-3 hours) reasonably well. The model also predicts the degree of the maximum DO stratification reasonably well. The DO model generally performs better near water surface and middle depths than at pond bottom. The model is very sensitive to the chlorophyll *a* related coefficients (μ_{max}, k_r, I_{opt}, T_{opt}, $Chla_{init}$) and physical processes (W, PAR, HKmax, η_o). The model is also sensitive to the SOD. The model is not sensitive to the BOD related processes and prawn related coefficients. The model is very sensitive to whether the chlorophyll *a* is simulated or not. On the contrary, there is no effect on the DO structure whether BOD is simulated or not. Varying the coefficients more or less changes the magnitude of the maximum DO stratification, but in most cases the timing of the maximum stratification remains the same. To simulate DO accurately, it is essential to simulate the chlorophyll *a* accurately. On the contrary, BOD variations (both spatial and temporal) are small. In modelling practice, BOD concentration can be fixed as a constant without reducing the accuracy of predicting DO.

ACKNOWLEDGMENTS

The work was funded by CRC for Aquaculture. We would like to thank N.Preston, C. Jackson, M. Burford and M. Austin of CSIRO Marine Laboratories at Cleveland QLD for assisting the data collection program. Special appreciation goes to Noel Herbs and Doug Dark of Gold Coast Marine Prawn Farm for their generous help during the data collection program.

REFERENCES

Busch, C.D., C.A. Flood, J.R. Koon, and R. Allison, 1977, Modelling catfish pond nighttime dissolved oxygen levels, *Trans. Amer. Soc. Agr. Eng.*, 20: 394-396.

Cassinelli, R.D., J.F. Farnsworth, V.E. Sweat, and D.L. Stoner, 1978, Variations in dissolved oxygen concentration in mariculture ponds - a preliminary model, p310-329, In Proceedings of the Third Annual Tropical and Subtropical Fisheries Technological Conference of the Americas, New Orleans, Louisiana, Texas A & M Sea Grant College Program, TAMU-SG-79-101.

Chang, W.Y.B., and H. Ouyang, 1988, Dynamics of dissolved oxygen and vertical circulation in fish ponds, *Aquaculture*, 74: 263-276.

Doherty, J., 1994, PEST: A unique computer program for model-independent parameter optimisation, Proceedings, Water Down Under 94 Conference, Vol. 1, 551-554.

Fang, X. and H.G. Stefan, 1995, Interaction between oxygen transfer mechanisms in lake models, *J. of Environmental Engineering*, Vol 121, No. 6.

Gao, J. and N.P. Merrick, 1996, Night time dissolved oxygen simulations in a marine aquaculture pond, Proceeding of paper presented at Aquaculture America'96, Arlington, Texas, USA, February 14-17, 1996 (Abstracts only).

Gao, J., 1997, Water quality modelling of aquaculture ponds, PhD Dissertation submitted to the University of Technology, Sydney.

Lorsordo, T.M., 1988, Characterization and modelling of thermal and oxygen stratification in aquaculture ponds, Ph.D. Dissertation, University of California, Davis.

Madenjian, C.P., G.L. Rogers, and A.W. Fast, 1987a, Predicting night time dissolved oxygen loss in prawn ponds of Hawaii: Part I Evaluation of traditional methods, *Aquacultural Engineering*, 6, 191-208.

Madenjian, C.P., G.L. Rogers, and A.W. Fast, 1987b, Predicting night time dissolved oxygen loss in prawn ponds of Hawaii: Part II A new method, *Aquacultural Engineering*, 6, 209-225.

Merrick, N.P., and J. Gao, 1997, Thermal stratification modelling of small shallow aquaculture ponds, this volume

Meyer, D.I. and D.E. Brune, 1982, Computer modelling of the diurnal oxygen levels in a stillwater aquaculture pond, *Aquacultural Engineering*, 1: 245-261.

Meyer, D.I., 1980, Modelling diel oxygen flux in a simulated catfish pond, M.S. thesis, University of California, Davis.

Riley, M.J., 1988, User's manual for the dynamic lake quality simulation model MINLAKE. External memorandum No. 213, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, MPLS, MN.

Riley, M.J., and H.G. Stefan, 1988, MINLAKE: A dynamic lake water quality simulation model, *Ecological Modelling*, 43, 155-182.

Romaire, R.P., C.E. Boyd, and W.J. Collis, 1978, Prediction of nighttime dissolved oxygen decline in ponds used for tilapia culture, *Trans. Am. Fish. Soc.*, 107:804-808.

Smith, D.W. and R.H. Piedrahita, 1988, The relationship between phytoplankton and dissolved oxygen in fish ponds, *Aquaculture*, 68:249-265.

Stefan, H.G. and X. Fang, 1994, Dissolved oxygen model for regional lake analysis, *Ecological Modelling*, 71:37-68.