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Evaluation of a Simulation Model for Predicting Early Morning Oxygen Depletion in Tropical Brackishwater Tilapia Ponds

HUGH W. THOMFORDE*

Brackishwater Aquaculture Center
College of Fisheries
University of the Philippines in the Visayas
Leganes, Iloilo, Philippines

Abstract - An early-warning simulation model developed by C.E. Boyd and colleagues to predict critical early-morning dissolved oxygen (DO) levels in fishponds was evaluated. DO lost or gained by diffusion was the most uncertain factor in solving the predictive equation, but appeared to vary consistently for all ponds according to wind conditions. Simple linear regression comparison between measured and predicted DO values at dawn, adjusted afterwards for diffusion, resulted in $r^2 = 0.94$ ($P < 0.01$). The absolute difference between actual and predicted early morning DO values was ≤ 0.34 $mg \cdot l^{-1}$, averaging 0.26 $mg \cdot l^{-1}$ or 15%, but values < 1 $mg \cdot l^{-1}$ varied by as much as 50%. If diffusion could be estimated more accurately, the model would be acceptable for general management purposes. A simple graphical projection method, plotting DO decline during the first hours of darkness versus time, and requiring no other information, was also evaluated, and found to predict DO depletion much less precisely under prevailing conditions, and with less advance warning.

A relatively simple method for predicting dissolved oxygen in ponds is of much practical interest to fish farmers. Using data from the scientific literature on diffusion, respiration by plankton, fish and benthic organisms, and BOD of manures, Romaire et al. (1978) predicted early morning DO in tilapia ponds, with or without daily manure inputs, within 10% of the actual concentrations, according to the following equation:

$$DO_t = DO_{dusk} \pm DO_{df} - DO_f - DO_m - DO_p - DO_{om}$$

where:

DO_t = DO after *t* hours of darkness

*Present address: Harbor Branch Oceanographic Institution, Division of Coastal, Environmental and Aquacultural Sciences, 5600 Old Dixie Highway, Ft. Pierce, Florida 34946, USA.

DO_{dusk}	=	DO at dusk
DO_{df}	=	gain or loss of O_2 by diffusion
DO_f	=	O_2 used by fish
DO_m	=	loss of O_2 to respiration by benthic organisms
DO_p	=	O_2 consumed by planktonic community and associated detritus
DO_{om}	=	O_2 consumed by organic manure

The present experiment adapted computations for predicting DO_m, DO_{om}, DO_f, DO_p and DO_{df} from equations and tabular functions of Schroeder (1975), Boyd et al. (1978) and Romaire et al. (1978) for Philippine brackishwater conditions.

The data necessary to solve the predictive equation include pond volume, salinity, temperature and DO of pond water at dusk, the number of hours until dawn, Secchi disk visibility (measured between 1000 and 1400 hours) or chemical oxygen demand (COD) of pond water, approximate BOD of daily organic inputs, and approximate fish standing crop and respiration rate. Secchi disk visibility can only be used to estimate oxygen consumption in ponds where plankton is the primary source of turbidity (Almazan and Boyd 1978). Alternatively COD may be used (Boyd 1973).

Another way of predicting DO decline is by projection (Boyd et al. 1978), a technique taking advantage of the generally linear decline in DO at night. It has been found almost as reliable for predicting DO decline (Boyd et al. 1978), and requires no knowledge of fish density or plankton respiration, but offers less warning time because estimates of DO decline cannot be made until 2–3 hours after dark. Where Secchi disk visibility cannot be used to estimate oxygen consumption by plankton, and COD analysis is not possible, this technique would be useful and was therefore evaluated.

The experiment was conducted in six 550-m^2 brackishwater earthen ponds at the Brackishwater Aquaculture Center, Leganes, Iloilo, Philippines. The ponds were subdivided into quarters by woven nylon 4 mm-mesh netting, and stocked with Nile tilapia, *Oreochromis niloticus*, for a concurrent experiment. During the main phases of this experiment, there were approximately 4,500–9,000 fish·ha^{-1}, weighing 52-114 g (average per pond), or 143–482 kg·ha^{-1}. Individual ponds were treated as single experimental units. Fresh chicken manure was added usually daily over the experimental period. The major part of the data for making and evaluating DO predictions was collected during two study periods: 15–19 December 1986, and 10–13 January 1987.

Early-morning DO predictions were made for one 550 m^2 pond stocked with Nile tilapia at 1.04 $t ha^{-1}$ during a third study period, 26 February-1 March 1987. This pond contained no benthic algae, and plankton production was stimulated by applying inorganic fertilizer. No manure was applied.

Water temperature and dissolved oxygen were monitored using a *YSI* Model 57 DO meter with stirrer at dusk, then several hours later, and then again at dawn (Fig. 1). The DO probe was suspended from the end of an 8-m pole, and measurements were made in deep water at eight stations around each pond near the top and bottom of the water column, and values averaged by pond.

Salinity was measured daily with a hand-held *Atago* salinity refractometer at two diagonally opposite corners per pond.

Secchi disk visibility was measured (without sunglasses) at 12 stations per pond between 1000 and 1400 hours daily. The 20-cm Secchi disk used was firmly mounted to a 2-m stick marked at cm intervals. At each station, three measurements were made about 0.5 m away from each other to avoid muddy water which was sometimes created by movement of the Secchi disk near the pond bottom. The rigid stick permitted the disk to be rotated so as to easily determine the depth at which the alternating black and white quadrants appeared or disappeared.

Water depth was monitored daily from permanent depth gauges marked every 5 cm, estimated by eye to the nearest cm.

Benthic respiration was assigned a constant value of 61 mg $O_2 \cdot m^{-2} \cdot hour^{-1}$, following Boyd et al. (1978). Given the shallowness of the ponds and prevailing weather, it was assumed that the pond bottoms were always oxygenated. The respiration rate multiplied by hours of darkness and pond size gave a value of respiration per liter for DO_m.

The chicken manure used for this experiment was estimated to have a 7-day BOD of about 40 g oxygen per kg wet manure at 30°C (Schroeder 1979). Thus, one kg of fresh chicken manure consumed about 4 g O_2 per 12-hour night. It takes 5-10 days (average, 7) for the manure to decay (Schroeder 1979). Since manure was broadcast usually daily, the cumulative BOD on a given day was the sum of the BOD of the new manure plus that of the previous 7 days, i.e., 28 g $O_2 \cdot kg^{-1}$ per night. Pro rata adjustments were made for some overcast days when no manure was applied.

Tilapia respiration was calculated by a general predictive equation (Winberg 1956) for fish respiration:

$$Y = 0.001 \cdot W^{0.82}$$

where Y = g of oxygen consumption per fish per hour and W = average weight of fish in g.

The value of DO_f was obtained by multiplying Y times the number of fish in the pond, times the number of hours from dusk to dawn, converted to $mg{\cdot}l^{-1}$. The rate of oxygen consumption was assumed to be independent of temperature for the range 20-30°C (Winberg 1956).

Oxygen consumption by plankton and associated detritus was determined by the empirical equation of Boyd et al. (1978) based on Secchi disk visibility and temperature:

$$DO_p\ (mg{\cdot}l^{-1}) = \text{hours to dawn} \cdot (-1.133 + 0.00381S + 0.0000145S^2 + 0.0812T - 0.000749T^2 - 0.000349ST)$$

where: S = Secchi disk visibility (cm) and T = water temperature at dusk (°C).

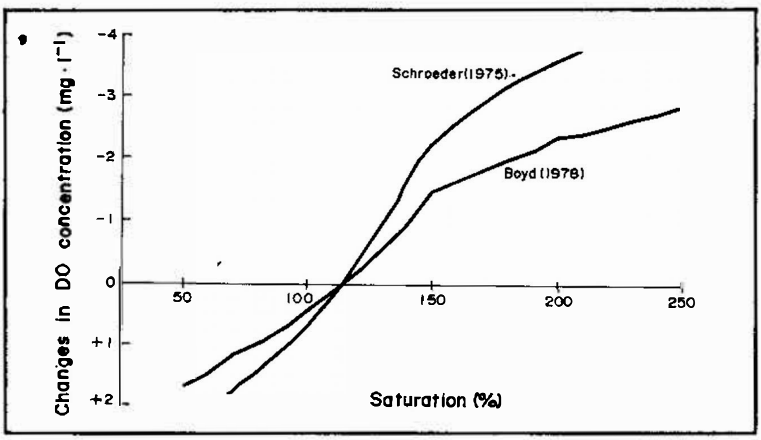

Fig. 1. Measured DO values (mg/l) versus time. Each point represents the grand mean of eight measurements from specific sampling stations in each of the six ponds, during one night. The data for 26 February-1 March, however, represents the grand mean of eight measurements, averaged over three nights, for only one pond. Where distinguishable, one standard error of the mean above and below each point is also indicated.

For the alternative method, COD was analyzed following the procedure for brackishwater in Golterman et al. (1978), using the McBride short-cut for $KMnO_4$ standardization (Day and Underwood 1980). The hourly rate of oxygen consumption ($mg{\cdot}l^{-1}\,hour^{-1}$) by plankton was estimated from COD and temperature according to the equation from Boyd et al. (1978):

$$O_2 \text{ consumption} = -1.006 - 0.00148C - 0.0000125C^2 + 0.0766T - 0.00144T^2 + 0.000253CT$$

where: C = COD ($mg{\cdot}l^{-1}$) and T = temperature (°C).

Using either Secchi disk visibility or COD, the value for DO_p was obtained by simply multiplying the oxygen consumption by the number of hours to dawn.

To predict the amount of oxygen gained or lost during the night by diffusion, it was necessary to determine the oxygen solubility in $ml{\cdot}l^{-1}$ ($mg{\cdot}l^{-1}\ O_2 = 1.428 \times ml{\cdot}l^{-1}\ O_2$), for each pond, based on water temperature and salinity using standard reference tables (e.g., Hawkins 1981). The saturation of the measured DO at dusk was determined by the equation:

$$\%\ \text{saturation} = \frac{\text{measured DO } (mg{\cdot}l^{-1})}{\text{oxygen solubility } (mg{\cdot}l^{-1})}\ 100$$

Then the predicted overnight (*not* hourly) changes in DO were obtained in tabular form from calm-weather data of Schroeder (1975) as modified by Boyd et al. (1978). Comparison of data from these two authors shown in Fig. 2 indicates that the value of DO_{df} may be more accurate if divided

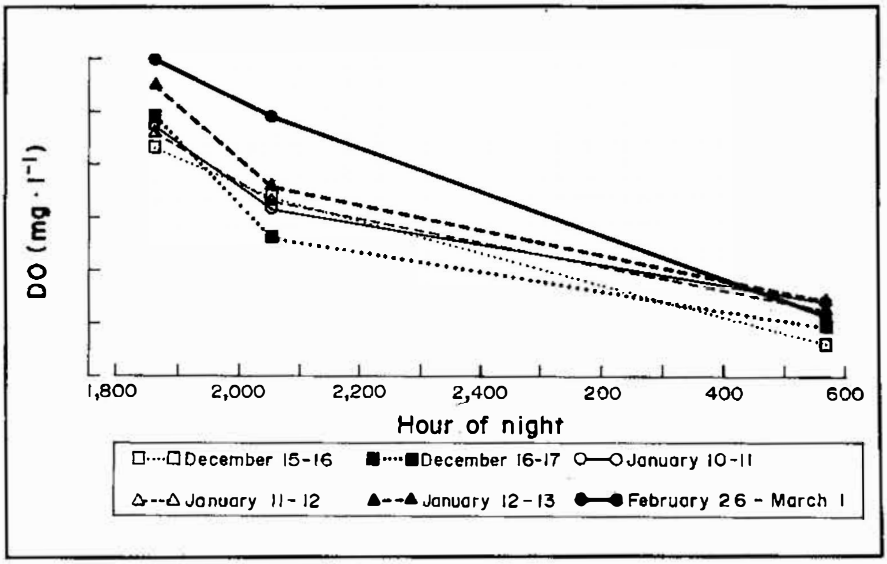

Fig. 2. Changes in DO concentration during the night in ponds with different dissolved oxygen saturation values at dusk. The graph indicates the predicted change in DO, according to Schroeder (1975, Fig. 1) for ponds 60-70 cm deep, and Boyd et al. (1978, Table 2) for ponds 1-m deep.

by pond depth. Values from different ponds obtained under uniform wind conditions on the same night were multiplied by a uniform adjustment factor to find the best fit of predicted and actual values.

Formulae to predict early-morning DO were incorporated on a *MULTIPLAN* software worksheet (available on request).

The ranges of water quality parameters during the study period are shown by pond in Table 1. During the two major study periods the night-time temperatures never exceeded the limits stipulated for Winberg's (1956) formula for fish respiration.

Table 1. Ranges of night-time water parameters monitored.

Date	Temperature (°C)	Salinity (ppt)	DO (mgl^{-1})	Depth (m)	Secchi vis (cm)
15-19 December	24.0-30.0	19-20	0.4-14.8	0.45-0.60	8-35
10-13 January	24.0-29.0	28-30	0.2-13.1	0.40-0.60	16.5-45
26 Feb-1 March	26.2-33.0	36-38	1.0-13.0	0.61-0.64	30-46

Differences between concurrent measurements of temperature, DO and Secchi disk visibility from different quarters of the same ponds were compared using analyses of variance and determined to be statistically insignificant ($P < 0.05$). Therefore, early morning DO was predicted only on a per pond basis.

Contrary to the findings of Boyd et al. (1978), DO levels during the night did not display a linear decline over time (Fig. 1). Thus, the slope method could not be used to predict DO. The most important insight from the graphs is that concurrent DO decline in the series of ponds varied in approximately the same manner for all ponds with respect to time. Inflection points in the DO decline curves probably indicated changes in wind conditions. An additional point of practical significance shown in Fig. 1 is that the predictions of early morning DO by extrapolation consistently resulted in *lower* values than those recorded.

DO_p calculated from COD data yielded values two or three orders of magnitude too low, possibly due to incorrect methodology, and was not useful in predicting early morning DO.

Predicting the amount of oxygen gained or lost by diffusion was clearly the most uncertain factor. Wind conditions apparently affected diffusion rates for all ponds simultaneously in a similar manner and to find the most accurate fit for the data, all DO_{df} values for the same night were multiplied by a uniform factor. By trial and error it was possible in all cases to determine a factor which reduced the absolute value of the

Table 2. Example of a comparison and analysis of early morning dissolved oxygen data derived by simulation and from actual measurement.

Dec. 15/16. Based on DO_{dr} Adjustment Multiple best fit of: 0.6

	DO at dawn ($mg \cdot l^{-1}$)		Difference	
Pond	Model	Actual	$mg \cdot l^{-1}$	%
A15	2.11	2.50	-0.39	-15.5
A16	0.79	0.81	-0.02	-2.2
A18	0.64	0.87	-0.23	-26.4
A22	1.17	1.13	0.04	3.9
A23	0.74	0.99	-0.25	-25.5
A24	0.75	0.82	-0.07	-8.1

Average absolute variation ($mg \cdot l^{-1}$): 0.17.

variance of the resulting discrepancy between actual and predicted DO_{dawn} to ≤ 0.34 (average 0.26) $mg \cdot l^{-1}$, with per cent error of ≤ 50% (average 15%).

Although Romaire et al. (1978) were usually able to predict DO at dawn with ≤10% error, they worked with a higher, less sensitive range (2.4-10 $mg \cdot l^{-1}$) than experienced during this study (0.3-5.8 $mg \cdot l^{-1}$). Both experiments generated predicted values very close to early morning DO. When fitted to simple linear regression ($P < 0.01$) Romaire et al. (1978) obtained a coefficient of determination (r^2) of 0.97 ($n = 36$). The present experiments yielded $r^2 = 0.94$ ($n = 42$) only after adjusting for diffusion (Fig. 3).

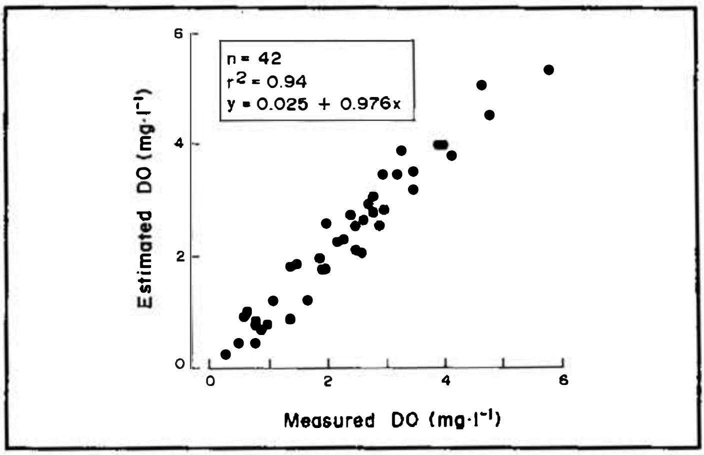

Fig. 3. Estimated versus measured early morning dissolved oxygen, 16-19 December 1986 and 11-13 January 1987, after adjusting for diffusion.

Romaire *et. al.* (1978) identified the primary reason for successful predictions to the reliable method of predicting plankton respiration, and the large contribution of plankton to the total DO loss (average 80% in manured ponds). It is interesting that their simulation model also generated accurate predictions in this experiment where high salinity caused DO_{df} to be a major factor under early evening conditions of high O_2 saturation, and DO_p was only 42–79% (average 61%) of total DO loss in manured ponds.

Predictions of DO in ponds with high fish biomass must be tested again with several concurrent replications. It was meaningless to adjust the diffusion factor for only one pond to an appropriate value, and obtain an exact fit of the predicted and actual values. Nevertheless, the adjustment multiples for 26 February-1 March (0.46, 0.86, 0.80) were all plausible values. This is not conclusive evidence that the model was predicting accurately for high fish biomass, but at least infers that probability. Much more meaningful data were generated by monitoring several pond budgets operating in series.

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