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Full Length Research Paper

A method for managing dissolved oxygen concentration during live hauling of channel catfish

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After experiencing difficulty in managing dissolved oxygen levels on several live hauls, a method has been developed for estimating the oxygen flow rate needed to sustain live channel catfish *Ictalurus punctatus* during transport. The mathematical model described in this paper provides aquaculturists, fish farmers, and fish haulers with an analytical method for estimating the oxygen flow rate needed to sustain a given biomass of channel catfish *I. punctatus* during transport. Based on peer-reviewed scientific literature, readily obtained data, and program in Microsoft© Excel, the model can be used for planning and evaluating dissolved oxygen management on live hauls.

Key words: Channel catfish, dissolved oxygen, live hauling, aquaculture.

INTRODUCTION

After experiencing difficulty in managing dissolved oxygen levels on several live hauls, a method has been developed for estimating the oxygen flow rate needed to sustain live channel catfish *Ictalurus punctatus* during transport. Model output includes equilibrium oxygen concentration with respect to ambient air temperature, local barometric pressure, estimated oxygen consumption for a given biomass over time, and comparison of predicted versus actual dissolved oxygen concentration for the duration of a live haul.

Fries et al. (1993) conducted an evaluation of an aeration system in a hauling tank loaded with 908 kg of channel catfish. The dissolved oxygen concentration at load out was >20 mg/L, dropped to less than 5 mg/L after 21 min, and finally to 2.2 mg/L at approximately 50 min. After correcting an electrical problem in the aeration system, dissolved oxygen concentration slowly increased, reaching saturation concentration of approximately 8 mg/L at 240 min.

In a study of the responses of hatchery-reared brook trout, lake trout *Salvelinus namaycush*, and splake *Salvelinus fontinalis x Salvelinus namaycush*, McDonald et al. (1993) measured dissolved oxygen concentration at the beginning and end of each of ten hauling trips, noting that dissolved oxygen levels were quite variable. Ending dissolved oxygen concentration was less than initial dissolved oxygen on four trips (-0.4 to -7.0 mg/L), and greater than initial dissolved oxygen concentration on six trips (+4 to +15 mg/L). McDonald et al. (1993) found that elevated dissolved oxygen concentration tended to be stressful based on the correlation between changes in oxygen concentration and cortisol level in brook trout.

Barton et al. (2003) conducted six actual hauls and one sham haul in a study of stress responses of juvenile walleye *Stizostedion vitreum.* Of three actual hauls conducted in South Dakota, ending DO was greater than initial DO by 13 mg/L on two hauls and by 6 mg/L on the third; ending DO was greater than initial DO by 10 mg/L for the sham haul. On three hauls conducted in Minnesota, ending DO was greater than initial by 3.0 mg/L on two hauls and 0.5 mg/L on the third.

Leggett et al. (2006) investigated stress response in diploid and triploid rainbow trout *Oncorhynchus mykiss* by conducting one transport treatment and one stationary treatment. Dissolved oxygen concentration was monitored periodically for the duration of each experiment, and oxygen flow was adjusted in an attempt to maintain a concentration of 10 to 20 mg/L. Dissolved oxygen concentrations were maintained at 10 to 20 mg/L (100 to

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200% saturation) in transport tanks, but ranged from 16 to 50 mg/L (150 to 460% saturation) in stationary tanks. Fish held in stationary tanks had significantly higher plasma cortisol and glucose levels than transported fish. Leggett et al. (2006) hypothesized that a confounding effect of hyperoxia was the cause.

Pearson et al. (2009) conducted four hauling trips during a study of the effect of loading density versus survival of golden shiners *Notemigonus crysoleucas*. At the end of the first trip, ending dissolved oxygen concentrations in the six hauling tanks ranged from 0.4 to 17 mg/L. In the tank having ending dissolved oxygen concentration of 0.4 mg/L, 32% (2.8 of 8.8 kg) of golden shiners died. On trips two, three, and four, ending dissolved oxygen concentrations ranged from 9.5 to >20, 17.4 to >20 and 15.7 to >20 mg/L, respectively. The weight of mortalities collected at the end of the last three trips was < 1% of the total fish weight transported.

Andrews and Matsuda (1975) developed an estimate of oxygen consumption for channel catfish held as 2.5 m diameter in tanks. Boyd et al. (1978) used data collected by Andrews and Matsuda (1975) to obtain an equation for estimating an hourly respiration of the channel catfish. The equation (Boyd et al., 1978) was used by Pearson and Beecham (2007) in a model to estimate the liquid oxygen volume needed to aerate a given biomass of fasted channel catfish. The mathematical model described in this paper provides aquaculturists, fish farmers, and fish haulers with an analytical method for estimating the oxygen flow rate needed to sustain a given biomass of channel catfish *Ictalurus punctatus* during transport. Based on peer-reviewed scientific literature, readily obtained data, and programmed in Microsoft© Excel, the model can be used for planning and evaluating dissolved oxygen management on live hauls.

METHODS

When developing the spreadsheet, an estimate of the mass of oxygen consumed by 1 kg of channel catfish of an average weight, held in water of a given temperature was obtained by Equation (1) derived by Boyd et al. (1978) from data originally collected by Andrews and Matsuda (1975).

$$\text{Log}_{10}\ \text{O}_2 \text{ consumption by channel catfish (g/kg fish/h)} = -0.999 - 0.000957\ W + 0.0000006\ W^2 + 0.0327\ T - 0.0000087\ T^2 + 0.0000003\ WT \ldots\ldots (1)$$

where, W = average channel catfish weight in g, and T = temperature (℃).

The equilibrium or saturation concentration for oxygen is computed using Equations (2) to /(4). Equation (3) (Colt, 1984) computes the Bunsen coefficient for oxygen. Equation (4) (Colt, 1984) computes the vapor pressure of fresh water. The solutions of Equations (3) and (4) are entered into Equation (2) (Colt, 1984; Kean, 2008) to obtain the equilibrium or saturation oxygen concentration. The form of Equation (2) found in Kean (2008) was used in the development of the spreadsheet. The forms of Equation (2) found in both Colt (1984) and Kean (2008) give the same result.

$$\text{C (oxygen) (mg/L)} = 1{,}000\ \beta K X(760 - P_{water})/760 \ldots\ldots (2)$$

where β = bunsen coefficient of oxygen (L/L atm); K = 1.42903 (conversion factor: ml/L to mg/L); X = 0.20946 (fraction of oxygen in atmospheric air), and P_{water} = vapor pressure of water (mmHg)

$$\text{Log}_e\ \beta = a_1 + a_2(100/T) + a_3 \log_e(T/100) + S[\,b_1 + b_2\,(T/100) + b_3\,(T/100^2)] \ldots\ldots (3)$$

$a_1 = -58.3877$; $a_2 = 85.8079$; $a_3 = 23.8439$; $b_1 = -0.034892$; $b_2 = 0.015568$; $b_3 = -0.0019387$; T = air temperature (Kelvin) = (273.15 +℃); S = salinity (‰), and $e_s = e_{st}10^Z$.

$$Z = a((Ts/T)-1 + b \log_{10}(Ts/T) + c(10^{d(1-(T/Ts))} - 1) + f(10^{h((Ts/T)-1)} - 1) \ldots\ldots (4)$$

where a = -7.90298; b = 5.02808; c = -1.3816E-7; d = 11.344; f = 8.1328E-3; h = -3.49149; e_{st} = local barometric pressure (mb); T_s = 373.16 Kelvin, and T = air temperature (Kelvin)

Ambient air temperature and barometric pressure for many localities are available from the United States National Weather Service (NWS). A hand-held electronic digital altimeter could also be used for finding these values while in the field.

In July 2008, model predictions were compared to actual data collected during a mock hauling trip conducted near Stuttgart, Arkansas. Weather data for June 30, 2008, was used to estimate ambient air temperature and barometric pressure for the test date (July 1, 2008). Water temperature measurements taken on June 30, 2008, were used to estimate water temperature on July 1, 2008. A simulated harvest was performed by fasting approximately 48 kg of USDA 103 line channel catfish (mean weight 53 g) for 48 h. Dip nets were used to capture fish held in two vats. The fish were transferred to three 1.2 m diameter vats containing fresh well water and salt (1.5‰), and held overnight. At 07:00 h the following morning, the fish were transferred to a 1.2 m diameter circular vat containing approximately 644 L fresh well water and salt (5‰). Oxygen flow to one AS202 ultra fine bubble ceramic diffuser (Aquatic Ecosystems, Apopka, Florida) was controlled by an acrylic flow meter (Key Instruments, Trevose, Pennsylvania) having range of 0.1 to 2.2 L/min. Documentation included with the diffuser stated that oxygen transfer efficiency for this diffuser is 40 to 55% at depth of 1 m. Water depth in the holding vat was 0.56 m, so oxygen transfer efficiency was estimated at 30%. The sensor probe of a YSI–550A dissolved oxygen meter (YSI Environmental Incorporated, Yellow Springs, Ohio), calibrated to 61 m elevation and 5‰ salinity in the vat at 07:30 h, was placed inside the vat and the vat was covered with a tarp. Dissolved oxygen concentration (mg/L and water temperature (ºC) were measured at 15 min intervals from 07:30 to 11:30 h.

RESULTS AND DISCUSSION

Microsoft© Excel was selected for this application because it is widely distributed and the programming code is straightforward. Individual users have control over the auto fill feature, so the prototype requires manual entry of repetitive data. No cells in the prototype are hidden, protected, or locked, so users may customize the spreadsheet by using auto fill, adding more rows or columns, or by applying other enhancements. Data is entered in rows 2 to 19; results are presented in rows 22 to 32 (Table 1). The exception to this rule is found in row18, where the dissolved oxygen concentration at the

Table 1. The oxygen management model for channel catfish at 16 time intervals.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
01	Input																	
02	Hauling tank	id	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
03	Transport date	mmddyy	070108	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
04	Interval number	n/a	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
05	Interval length	min	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
06	Begin (24 h)	time	730	745	800	815	830	845	900	915	930	945	1000	1015	1030	1045	1100	1115
07	End (24 h)	time	745	800	815	830	845	900	915	930	945	1000	1015	1030	1045	1100	1115	1130
08	Ambient air temperature	°C	22	22	23	23	24	24	25	25	26	26	26	26	27	27	27	28
09	Barometric pressure	mb	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022
10	Water in hauling tank	L	644	644	644	644	644	644	644	644	644	644	644	644	644	644	644	644
11	Sodium chloride	kg	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
12	Water temperature	°C	23	23	23	23	23	23	23	24	24	24	24	24	24	24	24	25
13	Total biomass	kg	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
14	Mean fish weight	g	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53
15	Estimated diffuser otr	percent	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
16	O_2 flow rate (selected)	L/min	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
17	O_2 flow rate (per meter)	L/min	1.3	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5
18	DO (at beginning of interval)	mg/L	4.7	5.9	7.7	7.8	8.2	8.5	9.0	9.5	10.8	11.8	12.0	11.3	10.3	9.8	8.8	8.0
19	DO (at end of interval)	mg/L	5.9	7.7	7.8	8.2	8.5	9.0	9.5	10.8	11.8	12.0	11.3	10.3	9.8	8.8	8.0	7.4
21	Results																	
22	Interval number	n/a	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
23	Cumulative transport time	min	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240
24	Salinity (g salt / kg water)	‰	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
25	Loading density	g/L	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75
26	O_2 consumed (per kg)	g//h	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6
27	O_2 consumed (total biomass)	L/min	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
28	O_2 flow rate (computed)	L/min	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1
29																		
30	Equilibrium concentration	mg/L	8.6	8.6	8.4	8.4	8.2	8.2	8.1	8.1	7.9	7.9	7.9	7.9	7.8	7.8	7.8	7.7
31	Predicted DO	mg/L	5.4	6.0	6.7	7.3	8.0	8.7	9.3	9.3	9.2	9.1	9.1	9.0	8.9	8.9	8.8	8.0
32	Measured DO	mg/L	5.9	7.7	7.8	8.2	8.5	9.0	9.5	10.8	11.8	12.0	11.3	10.3	9.8	8.8	8.0	7.4

Data is entered in rows 2 to19; results are presented in rows 22 to 32. This table was developed from a Microsoft© Excel spreadsheet.

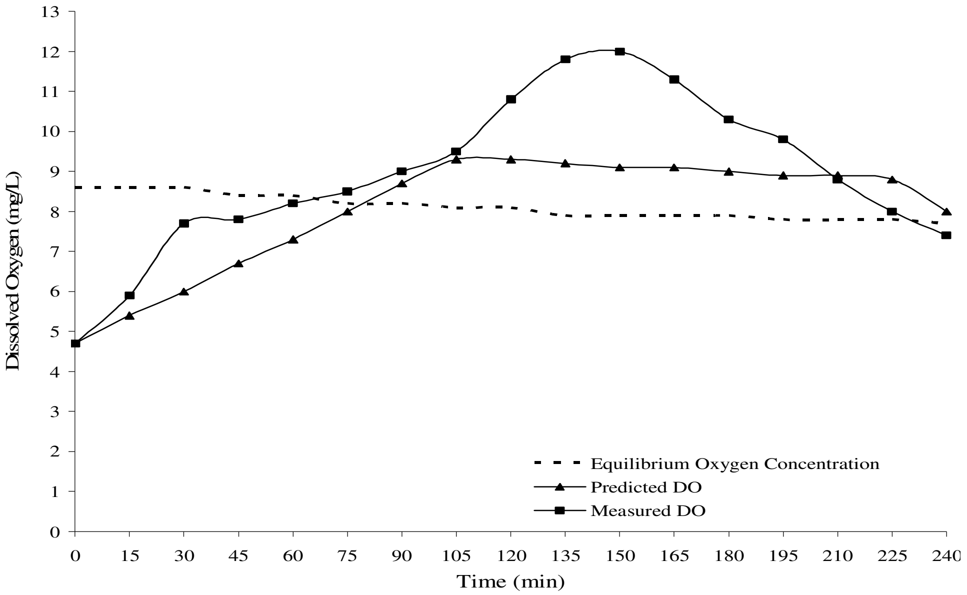

Figure 1. Equilibrium, predicted, and measured dissolved oxygen concentrations at 16 time intervals during a static test of an analytical model designed for management of dissolved oxygen levels while transporting live channel catfish.

beginning of the haul is entered in column C. Since the ending dissolved oxygen concentration for each interval is also the beginning dissolved oxygen concentration for the next interval, the value for cell D18, for example, was set to be equal to the value entered in cell C19.

Since the forms of Equation (2) found in both Colt (1984) and Kean (2008) give the same result, the form of Equation (2) found in Kean (2008) was used for this spreadsheet. The programming codes used in the model are as follows:

```
Oxygen consumption per kg fish per hour (Cell C26) =
10^((-0.999 -(0.000957*C14) + (0.0000006*(C14^2)) +
(0.0327*C12) - (0.0000087*(C12^2) + (0.0000003*C12)
```

and

```
Equilibrium concentration of oxygen (Cell C30) =
 ((EXP(-58.3877+85.8079*(100/(C8+273.15))+
23.8439*LN((C8+273.15)/100) + (C25*(-0.034892+
(0.015568*((C8+273.15)/100)) + (-0.0019387*(((C8+
273.15)/100)^2)))))))*0.393848*((C9*0.750064) -
(C9*10^(((-7.90298* ((373.16/ (C8+273.15)) - 1))) +
(5.02808*LOG(373.16 / (C8+273.15))) +
((((10^(11.344*(1-(C8+273.15)/373.16)))) - 1)*-
1.3816*10^-7) + (8.1328*10^-3*((10^(-3.49149*((373.16/
(C8+273.15))-1)) - 1))))*0.750064))
```

Cell definitions in Microsoft© Excel are entered with no spaces between characters or operators.

Channel catfish were predicted to have an average weight of 53 g and consume 0.5 g oxygen per kg fish per hour. The oxygen requirement for the 48 kg biomass was estimated at 0.28 L/min. If oxygen transfer efficiency of the diffuser was 30%, then a flow rate of approximately 1.0 L/min would provide adequate aeration. Dissolved oxygen in the circular vat was predicted to increase from 4.7 to 9.3 mg/L during the first 120 min, and then decrease to 8.0 mg/L at 240 min. The predicted range of water temperature was 22 to 28ºC. Barometric pressure of 1022 millibars was expected.

Actual water temperature ranged from 23 to 25ºC, and barometric pressure was steady at 1023 millibars during the test. The oxygen flow rate for interval one (0730 to 0745 h) is listed as 1.25 L/min. This is a weighted average for two rates used during that interval. Oxygen flowed at 4.0 L/min from 07:30 to 07:35 h, but flow was adjusted to 1.0 L/min at 07:35 h. Dissolved oxygen concentration (as measured) increased from 4.7 to 12.0 mg/L during the first 150 min. The steady increase for several intervals was observed, and then the oxygen flow rate was reduced to approximately 0.9 L/min at 120 min, 0.75 L/min at 135 min, and 0.5 L/min at 150 min. Dissolved oxygen concentration decreased from the 12.0 mg/L maximum to 7.4 mg/L at 240 min.

Channel catfish respiration was estimated at approximately 0.9 L/min (Table 1), and provided a margin of safety by introducing oxygen at one L/min (110% of estimated need). For the first five minutes of the experiment, however, the flow meter was set at four L/min (445% of predicted need) instead of 1 L/min. This error resulted in the rapid increase in dissolved oxygen concentration during the first 30 min of the experiment (Table 1 and Figure 1). A cumulative effect of aeration at 4 L/min from 1 to 5 min, and at 1.0 L/min from 6 to 105 min is the probable cause for the dissolved oxygen maximum of 12.0 mg/L at 150 min (Table 1; and Figure 1).

Conclusion

Evidence from scientific literature indicates that maintaining constant dissolved oxygen concentration during transport of live fish can be difficult. The Microsoft© Excel application discussed in this paper is an analytical method that should be useful in planning, conducting, and evaluating oxygen management on live hauls. The model estimates oxygen flow rates needed for aeration of channel catfish held in a hauling tank over time. We believe the model is adaptable for use with other species. Replacement of the channel catfish respiration equation with that for a selected species is the only modification required.

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