AQUACULTURE TECHNIQUES

PRELIMINARY STUDIES ON CARRYING CAPACITIES AND CENSUS-TAKING IN SERIAL REUSE PONDS

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AQUACULTURE TECHNIQUES:
PRELIMINARY STUDIES ON CARRYING CAPACITIES AND CENSUS-TAKING IN SERIAL REUSE PONDS

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ABSTRACT

Models for oxygen consumption by rainbow trout were developed and preliminarily tested under laboratory and field conditions. The major factor leading to inaccuracies in estimating population numbers was determined to be the sensitivity of measuring the dissolved oxygen entering and leaving the systems. Further studies are planned.

INTRODUCTION

Among the constraints to producing a high quality fish under intensively managed conditions is water quality and quantity (Klontz et al. 1978). In recent years, the increase in raising salmonids for food and conservation purposes has exceeded the supply of "new" water. This has necessitated the formulation of mathematical models to estimate carrying capacities; i.e., biomass life support, of fish rearing units (Klontz 1979). The models, for the most part, address the carrying capacities of single-use water systems. Multiple reuse systems wherein the water passes from one rearing unit into another for as many as 6-7 times have become quite popular because they do increase the producing capabilities of a unit of water. However, such systems have a high disaster potential if not managed properly. As water passes from one rearing unit to another, dissolved oxygen is diminished and waste products from the fish increase cumulatively. The frequent results are progressively reduced growth rates and increased noninfectious disease episodes, both which decrease the productivity of the system and increase production costs by reducing the feed conversion and the pounds per man-year produced.

The study addressed two major problems encountered in serial reuse raceway systems; namely, pond census-taking and stocking of ponds so that the life support capabilities were not exceeded in each reuse segment. These problems were identified during the studies to develop a systems approach to evaluating aquaculture facilities (Downey and Klontz 1982).

Subsequent definitions of the problems revealed that previous approaches to their resolution were inadequate because they did not take into account some of the key parameters, primarily the fish weight:water temperature-related standard metabolic rate (SMR). Other parameters not considered were oxygen recharge between serial reuse ponds, oxygen recharge along the course of an individual raceway pond, and the generation of fish-associated waste products such as ammonia and fecal solids.

The problem of estimating numbers of fish in a raceway pond, quite simply, is that the present methods are quite time consuming, stressful to the fish, and produce very erratic results (Klontz et al., 1978). All involve weighing and counting samples or subsamples of the population. The major errors arise from the samples and subsamples not representing the population, from weighing and counting errors, and from being able to account for cannibalism, bird predation, and escapees.

This study approached the problem in the following manner - if the SMR of a representative fish in the population were known and if the total dissolved oxygen consumption for a unit of time in the pond were known, then dividing the SMR value into the dissolved consumption should reveal the numbers of fish in the population. This concept is without precident in intensive aquaculture although several models for estimating SMR have been developed (Liao 1971, Beamish 1963, Mueller-Feuga et al. 1978, Klontz et al. 1978).

After examining the methods for determining the fish size and water temperature correlated methods of determining the SMR of salmonids, the following conclusions were made. The Klontz et al. (1978) model was developed for rainbow trout at 15°C, thus it was unsatisfactory for the purpose of this study. The Liao (1971) and the Mueller-Feuga et al. (1978) models were also considered to be unsatisfactory because they utilized quite different regression coefficients for the weight:water temperature slopes at water temperatures below 10°C and above 12°C.

The Liao model mathematically stated is:

$$O_u = K \times T^n \times W^m \qquad (1)$$

where: O_u = oxygen consumption in pounds of oxygen per 100 pounds of fish at size W in 24 hours

K = oxygen uptake rate constant

salmon $<50°F$ 7.2×10^{-7}
$>50°F$ 4.9×10^{-5}
trout $<50°F$ 1.9×10^{-6}
$>50°F$ 3.05×10^{-4}

T = water temperature (F)

W = fish weight (lb/fish)

n = water temperature slope

salmon $<50°F$ 3.20
$>50°F$ 2.12
trout $<50°F$ 3.13
$>50°F$ 1.86

M = fish weight slope

salmon $<50°F$ -0.194
$>50°F$ -0.194
trout $<50°F$ -0.138
$>50°F$ -0.138

The Mueller-Feuga et al. model mathematically stated is:

$$OD = \alpha \times p^{B} \times 10^{rt} \qquad (2)$$

where: OD = oxygen consumption per for 1 kg fish in mg/kg/hr

p = mean fish weight (g)

t = water temperature (°C)

α = regression coefficient

4-10°C 75

12-22°C 249

B = weight regression coefficient

4-10°C -0.196

12-22°C -0.142

r = water temperature regression coefficient

4-10°C 0.055

12-22°C 0.024

Thus, we decided to establish the curvilinear relationships between fish weight and water temperature. Once this was done, we then proceeded to evaluate the reliability and practicality of an oxygen consumption census-taking model. The final aspect of this study was to develop a model for loading fish into serial reuse raceway ponds so that neither life support nor waste product generation were limiting until an established point in time.

METHODS

1. Standard Metabolic Rate Determination:

a. Fish: Three groups of rainbow trout were established on the basis of their individual body weights. Group I consisted of fish weighing 4.4 +/- 0.4 g (mean body length - 73.1mm). Group II consisted of fish weighing 15.6 +/- 1.6 g (mean body length - 114.3mm).

The fish in Groups I and II were obtained as eyed eggs from a commercial source. They were hatched and subsequently maintained in the Wet Laboratory facilities in the Forestry Building, University of Idaho. The fish in Group III were obtained as first-feeding fry from the Washington Department of Game Trout Hatchery near Spokane, Washington.

Prior to being exposed to the test water temperature regimens, all three groups of fish were held in 13.5C water for two months. Prior to initiating the water temperature trials, all fish selected were examined individually for the presence of gross evidence of an existing clinical disease condition. Particular attention was given to the presence/absence of gill lamellar swelling. Clinically affected fish were discarded from further consideration in the experimental protocol.

b. Water: Three water temperature regimens (4.5C; 13.5C; 15.0C) were established using dechlorinated University of Idaho well water. The 13.5C and 15.0C temperatures were obtained by adjusting the on-line water temperature blending systems. The 4.5C temperature was obtained by a refrigerated recycled water system; i.e., biofiltration with a 1-2% make-up and an immersible refrigerator. This system was a modification of that described by Lai and Klontz (1980). The dissolved oxygen levels in all systems were maintained at 80-90% of saturation with exogenous seration.

c. Containers: Three systems of three glass aquariums (330mm x 330mm x 330mm) each were established (Figure 1). The aquaria in the 13.5C and the 15.0C systems were on single-pass water. The aquaria in the 4.5C system were on a recycled water system incorporating a plywood, fiberglass-lined biofiltration unit measuring 3.7m x 0.6m x 0.25m. The water flows to each aquarium were regulated to 1.89 lpm. This flow provided a 99% replacement time of 89 minutes (Downey, 1981).

d. Nutrition: Fish in all groups were fed 1/8" (3.175mm) Oregon Moist Pellet (OMP) diet several times daily. The daily amount of feed was calculated using the growth programming method of Haskell (1955). The daily increase in length (ΔL) estimation was based upon the 1.2mm daily Allowable Growth Rate (AGR) at 15C with a water temperature-corrected growth rate of 0.0825/°C decrease from 15C. The calculated feed conversion was 1.5:1

During the week following the introduction of the fish into their respective test systems, each sub group was fed at 60% AGR to minimize divergent growth among fish within the subgroup.

The fish in each test system were not fed for 24-36 hours prior to oxygen consumption measurements.

e. Health: After the oxygen consumption determinations, five fish from each subgroup were killed, exsanguinated, and fixed whole in 10% neutral-buffered formalin. After 24-30 hours fixation, a gill arch was

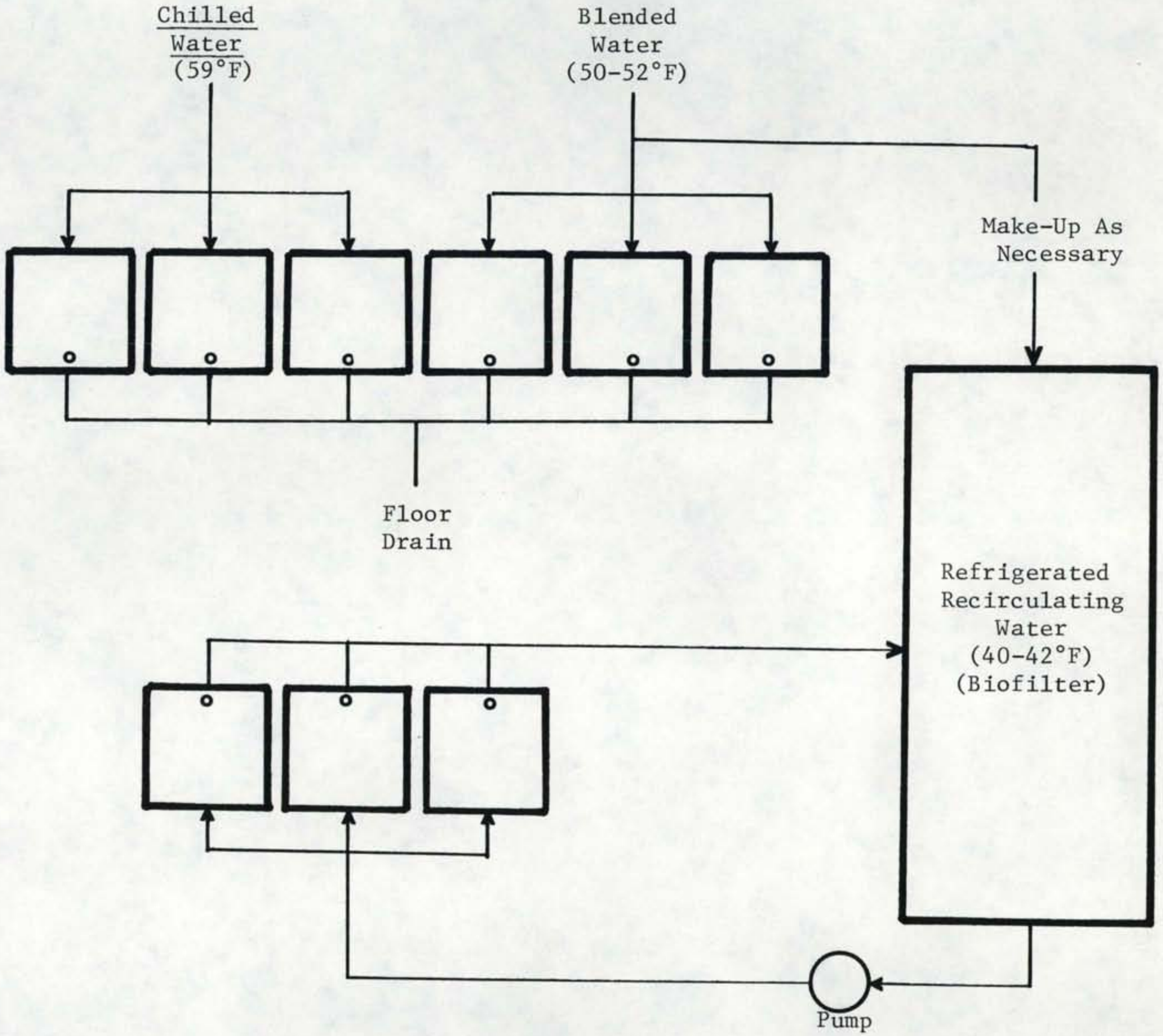

Figure 1. Schematic of experimental systems to measure oxygen consumption.

removed from each fish and preserved in 70% ethanol for subsequent paraffin imbedding and sectioning. In addition, fish were examined grossly for evidence of clinical disease at the end of each oxygen consumption trial.

f. Oxygen Consumption Determinations: The oxygen consumption trials were divided into three task sections: (1) premeasurement; (2) measurement; and (3) computational.

Premeasurement procedures consisted of:

(1) Eighty fish of the 4.4g size and 20 fish of each the 10.5g and 15.6g sizes were placed into each of the respective aquaria.

(2) The water temperature in each of the nine test aquaria was initially 13.5C. After the oxygen consumption data were collected, the water temperature was increased to 15C. After the 15C oxygen consumption data were collected, the water temperature was reduced to 4.5C at the rate of 2C/day.

(3) Prior to the oxygen consumption tests, the fish were acclimated to the systems for one week. Also, food was withheld for 24-36 hours prior to each test.

Measurement procedures consisted of:

(1) The aquarium water outfall pipe was stoppered, the aquarium filled to within 0.25 in., and the water inflow line removed (Fig. 2).

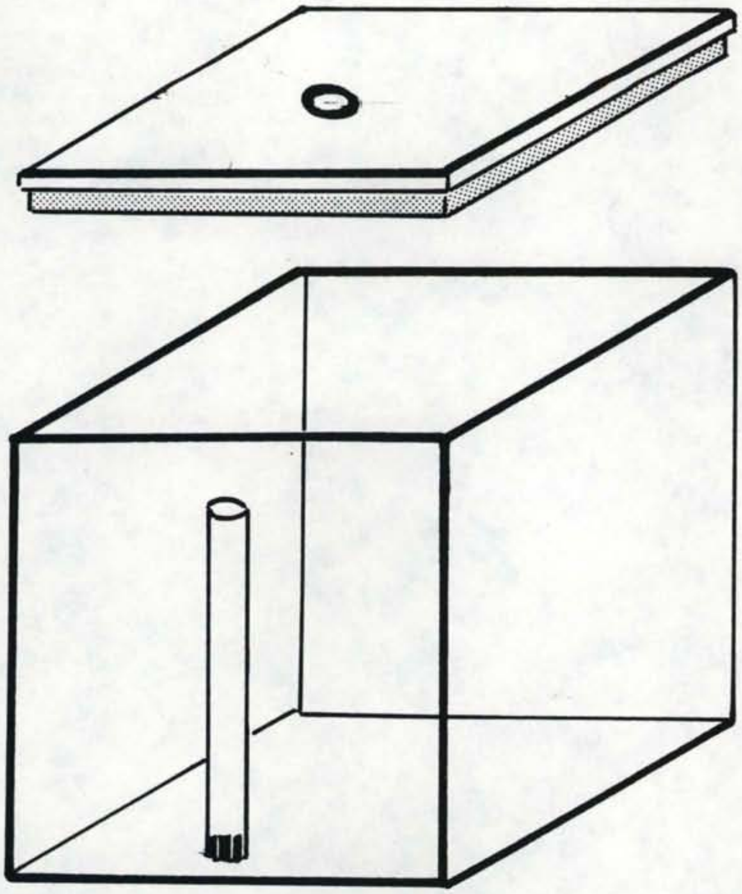

Figure 2. Oxygen consumption chamber (from Klontz et al., 1977). The stand-pipe was stoppered, the water inflow terminated when the water level reached within 1" of the top, and the tank covered with a foam-lined lid. Oxygen samples were obtained through the hole in the lid.

(2) The initial dissolved oxygen (Oi) concentrations (mg/l) in each aquarium were determined via the modified Winkler method.

(3) Each aquarium in turn was covered with a 12.7mm thick glass plate with a 1" (22mm) thick neoprene foam sheet attached to the underside. This effectively sealed the aquarium and prevented any reaeration at the air-water interface.

(4) At the end of a 30-minute period after sealing the aquarium, the lid was removed and duplicate water samples were taken for final oxygen (Oi) concentration (mg/l).

(5) The day following the oxygen consumption tests the fish were removed, killed, blotted dry, and weighed individually. Five fish from each group were fixed whole in 10% neutral buffered formalin for subsequent histopathological examination.

Computational procedures consisted of:

(1) The mean oxygen consumption (mg O_2/hour) by an individual fish was calculated by the following model:

$$\text{mg } O_2/\text{hr} = \frac{V(O_i - O_f)\ 60/t}{N} \qquad (3)$$

where: V = liters of water in test aquarium

O_i = mg/l dissolved oxygen at the beginning of the test

O_f = mg/l dissolved oxygen at the end of the test

N = number of fish in test aquarium

t = minutes between initial and final dissolved oxygen concentration determinations

(2) The mg O_2 consumed per hour per fish at each temperature was regressed against the log of individual fish weights to establish correlation coefficients.

2. Pond Census-taking Determinations:

a. Fish: Ten raceway populations of rainbow trout and four populations of cutthroat trout at three hatcheries were evaluated. The individual body weights in the 14 populations ranged from 1.04g to 164.5g. The age of the fish ranged from four weeks to one year. All populations were being raised on regulated feeding regimens. Prior to being evaluated, at least 10 fish were removed from each population and examined for evidence of clinical disease.

b. Water: Each population was being raised in open water systems; i.e., the water sources were from streams or reservoirs and not recycled. The temperatures ranged from 4.4C to 10.0C. Other water quality parameters were not documented.

c. Ponds: Each population was being raised in raceway ponds; i.e., the water enters one end of the pond. flows linearly through the pond, and exits over dam boards. The pond dimensions varied (Table 1).

d. Census-taking procedures: At the outset of each determination, pond inflow rates (lpm) were determined. These were measured using a standard weir table (Wood, 1974) or filling times. In turn, the maximum

Table 1. Raceway dimensions.

Raceway #	Location	Elev. (ft MSL)	Width (ft)	Depth (ft)	Length (ft)	Temp. (C)
1	DWR[1]	1000	8.0	2.3	65.0	4.4
2	"	1000	8.0	2.21	65.0	4.4
3	"	1000	8.0	2.3	65.0	4.4
4	"	1000	8.0	2.3	65.0	4.4
5	"	1000	8.0	2.3	65.0	4.4
6	"	1000	8.0	2.3	65.0	4.4
7	"	1000	8.0	2.3	65.0	4.4
8	DWR	1000	8.0	2.2	65.0	4.4
9	SPK[2]	2600	8.75	2.04	62.3	10.0
10	FRD[3]	1700	12.0	1.5	100.0	8.3
11	"	1700	3.9	1.7	28.4	8.3
12	"	1700	3.9	1.7	28.4	8.3
13	"	1700	3.9	1.7	28.4	9.44
14	FRD	1700	3.9	1.7	28.4	9.44

[1] Dworshak National Fish Hatchery, Orofino, Idaho

[2] Spokane Fish Hatchery, Washington Dept. Fish & Game, Spokane, Washington

[3] Ford Fish Hatchery, Washington Dept. Fish & Game, Ford, Washington

pond water velocities (fps) were calculated from the water inflow and the dimensions (Leitritz and Lewis, 1976).

Five replicate water samples from each end of the raceway were collected. Care was taken to avoid bias from dead areas and effervescent areas in the pond. Dissolved oxygen determinations were done on each sample using the sodium azide modification of the Winkler Method (APHA, 1975).

The mean fish weight in each population was determined by weighing several lots (50-175 fish/lot) from the upper, middle, and lower sections of the pond. After weighing the lot, the fish were anesthetized in 1:15,000 MS-222 (tricaine methanesulfonate, Allied) and weighed and measured individually. The mean body weight was calculated.

The water temperature was measured to the 10^{-1} C at both the inflow and outfall of the pond. In addition, the recorded daily water temperatures were examined for changes during the previous 14 days.

Table 2. The data necessary to calculate the oxygen consumption rate (mg O_2/hr) for each group of fish tested at each of three weight ranges and two temperatures. The experimental tank volume and time between initial and final oxygen concentrations was held constant at 36 liters and 30 minutes respectively.

$\overline{X}$ Weight (gms)	Temp. (C)	Rep. #	No. of fish	O_i (mg/l)	O_o (mg/l)	mg O_2/hr/fish
4.2	4.5	1	71	11.2	10.5	0.71
4.0		2	86	11.5	10.7	0.67
4.1		3	82	11.4	10.3	0.97
4.8	13.5	1	77	6.7	4.6	1.96
4.7		2	81	5.0	3.3	1.51
4.6		3	78	6.6	4.8	1.66
4.5	15.0	1	80	5.6	4.2	1.26
4.6		2	69	4.8	3.6	1.25
4.4		3	71	5.3	3.7	1.62
9.96	4.5	1	20	11.4	11.1	1.08
9.40		2	18	11.5	11.1	1.60
9.77		3	20	11.6	11.1	1.80
10.90	13.5	1	21	7.2	5.6	5.49
10.50		2	19	7.1	5.9	4.55
10.90		3	19	7.2	5.8	5.31
11.20	15.0	1	20	5.6	4.3	4.68
11.20		2	20	4.6	3.4	4.32
10.70		3	19	4.7	3.7	3.79
13.9	4.5	1	20	11.6	11.2	1.44
14.0		2	20	11.4	11.1	1.08
14.2		3	20	11.1	10.4	2.52
16.19	13.5	1	20	5.4	4.2	4.32
16.39		2	20	7.14	5.8	4.68
15.64		3	20	7.2	5.8	5.04
17.03	15.0	1	20	5.3	3.7	5.76
17.13		2	20	4.3	3.0	4.68
16.20		3	20	5.1	4.0	3.96

Temp - °C at time of test
Rep - replicate test number
$\overline{X}$ wgt - mean weight (g) per fish
No. - number of fish in replicate test
O_i - initial dissolved oxygen (mg/l)
O_o - final dissolved oxygen (mg/l) after 30'

RESULTS

1. Standard Metabolic Rate Studies:

Under constant water temperatures of 4.5, 13.5, and 15C, the oxygen consumption (OHF) in milligrams oxygen per hour per mean weight of individual fish was ascertained from the data summarized in Table 2 by the formula:

$$OHF = ((V*(Oi-Of))*(60/t))/N \qquad (4)$$

where: OHF = milligrams oxygen uptake per fish per hour

V = volume of water in the test tank (liters)

Oi = initial dissolved oxygen concentration (mg/liter)

Of = final dissolved oxygen concentration (mg/liter)

N = number of fish in the test aquarium

t = time between the initial and final oxygen measurements in minutes

Previous work by Klontz et al. (1978) indicated that the natural logarithm (log) of oxygen consumption (OHF) is linearly related to the natural logarithm of the individual weight in grams at a constant temperature 15C. This general relationship is described by the expression:

$$\log(OHF) = a + (b * \log(W)) \qquad (5)$$

where: W = weight per fish in grams

a = intercept for the log of oxygen consumption

b = slope of the line

Converting OHF and weight of the fish from Table 2 into natural logarithms and using the relationship of equation 5, regressions were performed using the log(OHF) against log weight (grams) for each individual temperature. Values were obtained for the regression coefficients (a,b) and the coefficient of determination (R^2). These coefficients for the regressions are:

Temperature	a	b	R^2
4.5	-1.080	.6060	.60
13.5	-1.132	.9982	.83
15.0	-0.774	.8990	.91

We then tested the significance of the slopes of the regressions of oxygen consumption and body weight. An analysis of covariance indicated a significant difference (P=.05) between the regression coefficients at 4.5C and the 13.5 and 15.0, but we found no significant difference between the slopes for 13.5 and 15.0C.

In order to obtain a predictive equation applicable for different weights of rainbow trout at different temperatures, a multiple regression model was computed. We used the log of oxygen consumption per hour per fish against the log weight and temperature as independent variables. A curvilinear relationship was found and is described by the equation:

$$\log(OHF) = a + (b*\log(W)) + (c*T) \qquad (6)$$

where: a = intercept for the log of oxygen consumption

b = regression coefficient for log(W)

W = individual weight per fish in grams

c = regression coefficient for temperature

T = water temperature in degrees centigrade

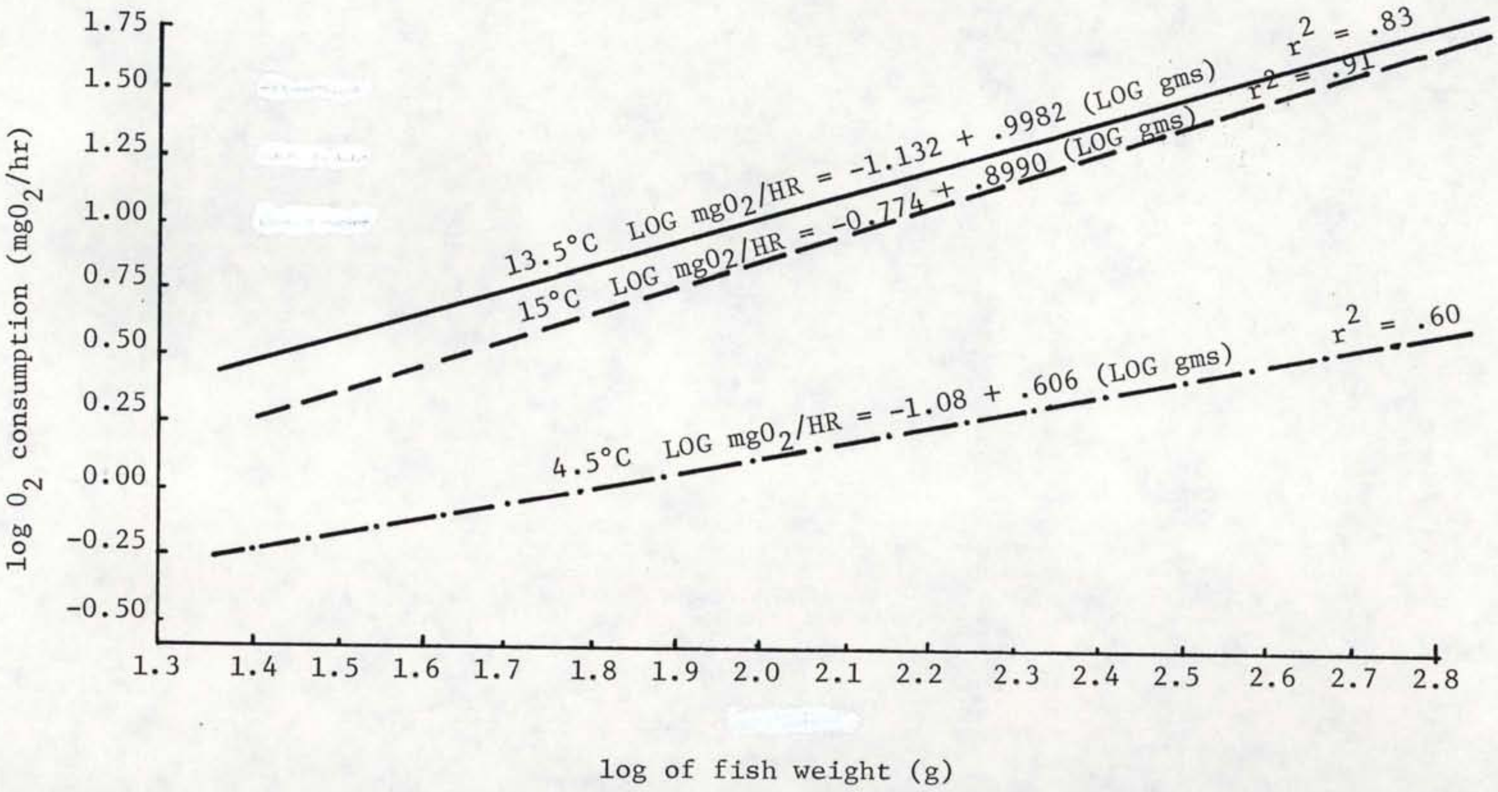

Figure 3. Oxygen consumption of rainbow trout at different temperatures.

The derived regression model provided a high degree of predictability accounting for 86% of the variation in oxygen consumption. The coefficient of determination and the derived regression coefficients values are:

$$R^2 = .855$$

$$a = -.84753166$$

$$b = 0.84281471$$

$$c = .03733078$$

Substitution of regression coefficients into equation 3 yielded a predictive equation which forecasts the logarithm of the oxygen consumption for an individual fish of a specific weight at a given acclimation temperature:

$$\log(\mathrm{OHF}) = -0.847532 + 0.8428(\log(W)) + 0.03733 \qquad (7)$$

Comparison of the predicted values for equation 4 with rearing temperature held constant at 15.0C to the predicted oxygen consumption values obtained a model developed by Klontz et al. (1978):

$$\log(\mathrm{OHF}) = -0.3128 + 0.8423(\log(\mathrm{weight})) \qquad (8)$$

A correlation coefficient of 1.0 was obtained for temperature values of 15°C and random weights indicating an allowable substitution could be made for equation 5 for temperatures different than 15°C with equation 4.

Identical sets of random hypothetical weight and temperature data to predict the individual oxygen consumption rates (OHF) were used for equation (4) and similar regressions reported by Mueller-Fuega (1980) with a resulting correlation coefficient of .98685 ($p<.0001$). No significant differences could be found between the predicted values ($p=.05$).

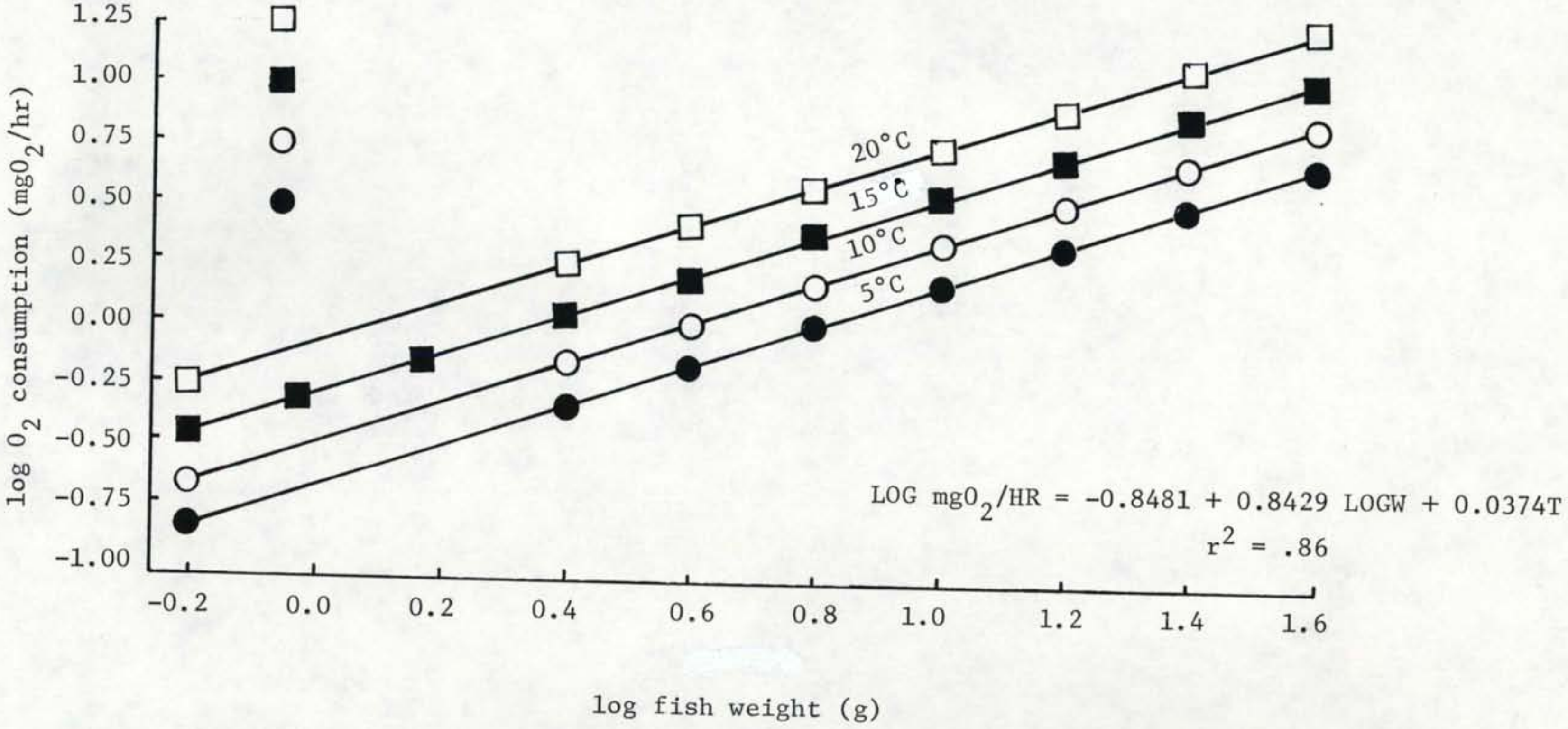

Figure 4. Predicted curves for oxygen consumption at different temperatures.

2. Pond Census-Taking Studies:

a. Derivation of models for the procedure: The oxygen content of a raceway at any point in time is determined by the inflow concentration, the water's ability to hold oxygen, the rate at which the oxygen is consumed, and the rate at which it is replaced (Brown, 1980). Limnologists and hydrologists have used this rationale for predicting oxygen concentrations at certain points along a natural stream, and it could serve the same purpose for fish culturists. However, in a natural stream biochemical and chemical oxygen demand (BOD and COD) are considered to be the major losses or "sinks" of oxygen whereas in a hatchery raceway the fish oxygen demand (FOD) becomes the major "sink." BOD and COD are also acting in a raceway, but if the raceway is concrete (vs. dirt bottomed) and kept clean, BOD and COD become negligible relative to FOD. To estimate the number of fish by how much oxygen they consume, it is necessary to account for the various sources and sinks of oxygen in a raceway, calculate the FOD, and determine the number of fish necessary to produce the FOD.

The change in dissolved oxygen concentration in a raceway can be expressed by the following differential equation:

$$\frac{dDO}{dt} = (K2\ D)--FOD \qquad (9)$$

where: K2 = the reaeration constant of the raceway by diffusion of oxygen from the atmosphere, follows Henry's Law, and is calculated by:

$$K2 = \frac{K1\ Rv^{n}}{H^{m}\ 3600} \qquad (9a)$$

Where: Kl = constant 5.9*   * Values from Churchill (1962)

Rv = water velocity (fps)

H = water depth (ft)

n = constant 1.0*

m = constant 1.7*

3600 = conversion factor for seconds to hours

D = the oxygen deficit of the water (mg/l) and is calculated by:

$$D = (DO_{sat} - DO_i) \qquad (9b)$$

Where: DO_{sat} = the saturation dissolved oxygen concentration (mg/l) adjusted for temperature and elevation (Table 3).

DO_i = the measured initial or inflow dissolved oxygen concentration of the raceway

FOD = fish oxygen demand (mg/hr). Empirically derived in Phase 1 and even though it will change with time in this differential equation, the time interval is so short, FOD is considered a constant. FOD is calculated by:

$$FOD = \frac{N(W^b\ 10^{a+cT})}{Vol} \qquad (9c)$$

Where: N = the number of fish in the raceway

W = the average weight per fish (gms)

T = water temperature (C)

Vol = rearing volume of the raceway (only that volume which is available to fish)

Table 3. Solubility of oxygen in pure water at equilibrium with moist air.

Water Temperature °C	Elevation (in feet above msl)					
	0	1000	2000	3000	4000	5000
0	14.63	14.08	13.55	13.04	12.57	12.10
1	14.23	13.69	13.17	12.68	12.22	11.77
2	13.84	13.32	12.81	12.33	11.89	11.44
3	13.46	12.95	12.46	11.99	11.56	11.13
4	13.11	12.61	12.14	11.68	11.26	10.84
5	12.77	12.29	11.82	11.38	10.97	10.55
6	12.45	11.98	11.52	11.09	10.69	10.29
7	12.13	11.67	11.23	10.80	10.41	10.02
8	11.84	11.39	10.96	10.55	10.16	9.78
9	11.55	11.11	10.69	10.29	9.91	9.54
10	11.28	10.85	10.44	10.05	9.68	9.32
11	11.02	10.60	10.20	9.81	9.46	9.10
12	10.77	10.36	9.97	9.59	9.24	8.89
13	10.53	10.13	9.74	9.37	9.03	8.69
14	10.29	9.90	9.52	9.16	8.83	8.49
15	10.07	9.69	9.32	8.96	8.63	8.81
16	9.86	9.48	9.12	8.77	8.45	8.13
17	9.65	9.28	8.93	8.59	8.27	7.96
18	9.46	9.10	8.75	8.42	8.11	7.80
19	9.27	8.91	8.57	8.25	7.94	7.64
20	9.08	8.73	8.40	8.07	7.78	7.48

a = constant -0.84753166* * Values from SMR studies

b = constant 0.84281471

c = constant 0.03733078

By integrating equation (1) and solving for DO, the following equation expresses the dissolved oxygen concentration in the raceway at any point in time:

$$DO_o = \left(DO_i - \frac{K2 \cdot DO_{sat} - FOD}{K2}\right) e^{-K2 \cdot tr} + \frac{K2 \cdot DO_i - FOD}{K2} \qquad (10)$$

Where: DO_o = the raceway outflow dissolved oxygen concentration (mg/l)

DO_i = the raceway inflow dissolved oxygen concentration (mg/l)

DO_{sat} = the saturation dissolved oxygen concentration

$K2$ = the reaeration constant (equation 9a)

FOD = the fish oxygen demand (mg/hr) (equation 9c)

tr = the replacement time (hrs). That time necessary for one turnover of the raceway water volume calculated by:

$$tr = \frac{Vol}{Rw\ 3600} \qquad (10c)$$

Where: Vol = total rearing volume (ft^3)

Rw = water inflow rate (cfs)

3600 = conversion from seconds to hours

By solving equation (10) for the FOD, the following equation estimates the number of fish in a raceway:

$$N = \frac{K2 \cdot DO_{sat} - K2\ (DO_o - DO_i e^{-K2tr}) \cdot Vol}{(1 - e^{-K2tr})\ (W^b \cdot 10^{a+cT})} \qquad (11)$$

Where: N = the number of fish in the raceway

Vol = rearing volume (liters)

$K2$ = reaeration constant (equation 9a)

DO_{sat} = saturation dissolved oxygen concentration (mg/l)

DO_i = inflow dissolved oxygen concentration (mg/l)

DO_o = outflow dissolved oxygen concentration (mg/l)

tr = replacement time (hrs) (equation 10a)

T = water temperature (C)

W = average weight per fish (gms)

a = constant -0.84753166

b = constant 0.84281471

c = constant 0.03733078

By collecting the necessary data to compute equation (11), the number of fish in a raceway can be estimated.

b. Application of Models: We were able to predict the numbers of fish to within an average of ± 16% of the hatchery inventory records for rainbow trout (Table 4). The inaccuracy of our estimates may have been due in part to the variability in parameter measurement as well as inaccuracy in the hatchery record estimates. Because of necessity, we had to rely on the hatchery records for the actual number of fish. It should be noted that only two raceways (#9 and #10, Table 4) had been inventoried for at least five months prior to this study although they were scheduled to be enumerated and stocked as this report is being prepared. For raceways #1-#8, mortalities had been recorded from the time they were stocked but a 15% discrepency in numbers upon harvest would not be uncommon (Jerry McClain, personal communication).

Table 4. Estimates of numbers of rainbow trout in 10 raceway pond populations using the developed oxygen consumption method.

Pond No.	Temp (^{o}C)	Water Inflow (cfs)	x g/fish	D.O. (mg/1) inflow	D.O. (mg/1) outfall	Population actual	Population estimate
1	10.0	0.400	1.04	8.2	7.0	175,000	141093
2	8.3	0.46	90.0	10.1	6.7	15,200	12,260
3	4.4	1.27	140.07	12.4	11.8	7,719	5,794
4	4.4	0.91	164.5	12.3	10.9	8,165	8,492
5	4.4	0.91	142.7	12.0	11.3	8,222	4787
6	4.4	1.28	139.6	12.4	11.3	8,848	10,778
7	4.4	1.32	154.1	12.2	11.8	4,762	3,719
8	4.4	1.27	146.3	12.1	11.3	7,617	7,476
9	4.4	1.17	155.6	12.2	11.1	7,709	8,991
10	4.4	0.92	134.1	11.8	10.7	6,432	8,014

Legend:

Pond Nos.	Location
1	Spokane Trout Hatchery, WDG
2	Ford Trout Hatchery, WDG
3	Dworshak NFH - no. 5A
4	Dworshak NFH - no. 5B
5	Dworshak NFH - no. 6A
6	Dworshak NFH - no. 6B
7	Dworshak NFH - no. 7A
8	Dworshak NFH - no. 7B
9	Dworhsak NFH - no. 8A
10	Dworshak NFH - no. 8B

Although the decrease in dissolved oxygen concentrations along the length of a raceway can be expressed finitely, i.e., ΔDO rather than continuously as $\frac{dDO}{dt}$, the differential form better explains the changes in dissolved oxygen occurring. The diffusion of oxygen into a raceway follows Henry's law and can be expected to increase as the FOD decreases the partial pressure of oxygen in the water. Although this increase is negligible (e.g., 0.02 mg/l for a 65 ft. by 8 ft raceway), it was taken into account because the FOD function was derived using a closed respirometer which did not allow reaeration. The FOD values corrected with the predicted reaeration with FOD values given by functions derived directly in raceway situations by Liao (1968) and Mueller-Feuga et al. (1978). Using a Chow test (Chow, 1960), there were no significant differences (p=0.05) between our model and those models derived in raceways. It was noted that a difference of several hundred fish would result if the reaeration function were not included.

3. Multiple Reuse Pond Loading Studies:

a. Oxygen demand of fish: Initially, the days to elapse between pond stocking and population reduction must be established. It is advisable that at least three 14-day growth periods or 42 days be used. Next, the Allowable Growth Rate (AGR) of the fish should be calculated. The AGR, expressed as either mm/day or in./day, is then multiplied by the number of days the fish will remain in the ponds. The result, the length increase during the time, is added to the length of the fish on hand, thus giving the length of the fish at population reduction time.

Table 5. Weight: Length Table for Rainbow Trout in Production Conditions - English Units

Length Inches	Weight Lbs.	Number per Pound	Condition Factor
1.250	0.000659	1516.97705	0.00033751
1.500	0.001166	857.50684	0.00034553
1.750	0.001889	529.38892	0.00035246
2.000	0.002869	348.60229	0.00035857
2.250	0.004147	241.14874	0.00036406
2.500	0.005766	173.42807	0.00036903
2.750	0.007769	128.70959	0.00037359
3.000	0.010201	98.03439	0.00037780
3.250	0.013103	76.31587	0.00038171
3.500	0.016523	60.52229	0.00038537
3.750	0.020504	48.77162	0.00038881
4.000	0.025092	39.85387	0.00039206
4.250	0.030332	32.96808	0.00039513
4.500	0.036272	27.56931	0.00039805
4.750	0.042958	23.27866	0.00040083
5.000	0.050436	19.82712	0.00040349
5.250	0.058754	17.02013	0.00040603
5.500	0.067959	14.71467	0.00040847
5.750	0.078100	12.80409	0.00041082
6.000	0.089224	11.20775	0.00041307
6.250	0.101380	9.86390	0.00041525
6.500	0.114616	8.72482	0.00041735
6.750	0.128981	7.75307	0.00041939
7.000	0.144525	6.91922	0.00042136
7.250	0.161297	6.19975	0.00042327
7.500	0.179347	5.57580	0.00042512
7.750	0.198723	5.03214	0.00042692
8.000	0.219476	4.55630	0.00042867
8.250	0.241659	4.13807	0.00043037
8.500	0.265318	3.76906	0.00043203
8.750	0.290506	3.44228	0.00043364
9.000	0.317274	3.15185	0.00043522
9.250	0.345672	2.89291	0.00043676
9.500	0.375752	2.66133	0.00043826
9.750	0.407566	2.45359	0.00043973
10.000	0.441163	2.26673	0.00044116
10.250	0.476597	2.09821	0.00044257
10.500	0.513920	1.94583	0.00044394
10.750	0.553184	1.80772	0.00044529
11.000	0.594440	1.68225	0.00044661
11.250	0.637743	1.56803	0.00044791
11.500	0.683140	1.46383	0.00044918
11.750	0.730690	1.36857	0.00045042
12.000	0.780442	1.28132	0.00045165

Table 6. Weight: Length Table for Rainbow Trout in Production Conditions - Metric Units

Length mm.	Weight gm.	Number per kgm	Condition Factor	Weight per 1000 kgms
30.	0.250	3993.41675	0.00000932	0.250
35.	0.406	2465.36865	0.00000950	0.406
40.	0.616	1623.44312	0.00000967	0.616
45.	0.890	1123.03125	0.00000982	0.890
50.	1.238	807.65601	0.00000995	1.238
55.	1.668	599.40015	0.00001007	1.668
60.	2.190	456.54639	0.00001019	2.190
65.	2.814	355.40308	0.00001029	2.814
70.	3.548	281.85254	0.00001039	3.548
75.	4.403	227.12967	0.00001048	4.403
80.	5.388	185.60033	0.00001057	5.388
85.	6.513	153.53235	0.00001065	6.513
90.	7.789	128.39026	0.00001073	7.789
95.	9.224	108.40904	0.00001081	9.224
100.	10.830	92.33525	0.00001088	10.830
105.	12.616	79.26282	0.00001095	12.616
110.	14.593	68.52649	0.00001101	14.593
115.	16.770	59.62889	0.00001108	16.770
120.	19.159	52.19461	0.00001114	19.159
125.	21.769	45.93628	0.00001120	21.769
130.	24.611	40.63142	0.00001125	24.611
135.	27.696	36.10600	0.00001131	27.696
140.	31.034	32.22279	0.00001136	31.034
145.	34.635	28.87222	0.00001141	34.635
150.	38.511	25.96660	0.00001146	38.511
155.	42.672	23.43466	0.00001151	42.672
160.	47.128	21.21867	0.00001156	47.128
165.	51.891	19.27106	0.00001161	51.891
170.	56.971	17.55254	0.00001165	56.971
175.	62.380	16.03069	0.00001169	62.380
180.	68.128	14.67822	0.00001174	68.128
185.	74.226	13.47235	0.00001178	74.226
190.	80.685	12.39382	0.00001182	80.685
195.	87.516	11.42541	0.00001186	87.516
200.	94.730	10.55618	0.00001190	94.730
205.	102.339	9.77135	0.00001193	102.339
210.	110.354	9.06172	0.00001197	110.354
215.	118.785	8.41853	0.00001201	118.785
220.	127.644	7.83426	0.00001204	127.644
225.	136.942	7.30232	0.00001208	136.942
230.	146.690	6.81705	0.00001211	146.690

Table 6, Cont'd.

Length mm.	Weight gm.	Number per kgm	Condition Factor	Weight per 1000 kgms
235.	156.900	6.37344	0.00001215	156.900
240.	167.583	5.96714	0.00001218	167.583
245.	178.751	5.59433	0.00001221	178.751
250.	190.415	5.25165	0.00001224	190.415
255.	202.586	4.93614	0.00001227	202.586
260.	215.276	4.64518	0.00001231	215.276
265.	228.495	4.37643	0.00001234	228.495
270.	242.257	4.12782	0.00001237	242.257
275.	256.572	3.89751	0.00001239	256.572
280.	271.453	3.68386	0.00001242	271.453
285.	286.909	3.48540	0.00001245	286.909
290.	302.954	3.30081	0.00001248	302.954
295.	319.599	3.12890	0.00001251	319.599
300.	336.854	2.96862	0.00001253	336.854
305.	354.733	2.81900	0.00001256	354.733
310.	373.249	2.67916	0.00001259	373.249
315.	392.409	2.54834	0.00001261	392.409
320.	412.229	2.42582	0.00001264	412.229
325.	432.719	2.31095	0.00001266	432.719
330.	453.890	2.20316	0.00001269	453.890
335.	475.756	2.10190	0.00001271	475.756
340.	498.329	2.00669	0.00001274	498.329
345.	521.618	1.91710	0.00001276	521.618
350.	545.638	1.83270	0.00001279	545.638
355.	570.399	1.75315	0.00001281	570.399
360.	595.914	1.67808	0.00001283	595.914
365.	622.194	1.60720	0.00001285	622.194
370.	649.253	1.54022	0.00001288	649.253
375.	677.101	1.47687	0.00001290	677.101
380.	705.751	1.41692	0.00001292	705.751
385.	735.215	1.36014	0.00001294	735.215
390.	765.503	1.30632	0.00001296	765.503
395.	796.632	1.25528	0.00001299	796.632
400.	828.609	1.20683	0.00001301	828.609
405.	861.450	1.16082	0.00001303	861.450
410.	895.161	1.11711	0.00001305	895.161

The number per pound of this size fish is then determined from the appropriate length:weight table. From the number per pound, the mean weight of an individual fish in grams can be calculated (Tables 5 & 6).

The standard metabolic rate (SMR) in mg/0_2 uptake/hr. for an individual fish is then calculated using the following model:

$$\text{Log } Y = -0.84753166 + 0.84281471 \text{ Log } X + 0.03733078 \qquad (12)$$

Where: Y = oxygen requirement (mg/hr.) for a fish of size X

X = average weight (g) per fish

T = water temperature (^{o}C)

b. Oxygen availability in pond: The following calculations must be made:

1. Total pond volume: $L \times W \times D = \text{ft}^3$
2. Water inflow: Filling time for a specified volume

   Cubic feet per second x 28.32 = liters per second (lps)
3. Liters per hour inflow: lps x 3600
4. Dissolved oxygen (mg/l) inflow: From Table 3 or by measurement
5. Mg/hr. dissolved oxygen: lph x mg/l D.O._{in}
6. Dissolved oxygen (mg/l) at 90 mm Hg $\text{p}0_2$ in outfall; From Table 7

c. Carrying capacity estimation:

Deck 1 (upper)

D.O._i	mg/l 0_2 of incoming water
ΔDO	30% reduction of D.O._i
D.O._o	$\text{D.O.}_i - \Delta\text{DO}$

Recharge - 10% of D.O._i

Table 7. The dissolved oxygen content (in mg/l) at various temperatures and elevations which exert an oxygen partial pressure of 90 mmHg.

Water Temperature °C	Elevation (in feet above msl) 0	1000	2000	3000	4000	5000
0	8.32	8.32	8.32	8.32	8.32	8.32
1	8.10	8.10	8.10	8.10	8.10	8.10
2	7.88	7.88	7.88	7.88	7.88	7.88
3	7.66	7.66	7.66	7.66	7.66	7.66
4	7.47	7.47	7.47	7.47	7.47	7.47
5	7.28	7.28	7.28	7.28	7.28	7.28
6	7.10	7.10	7.10	7.10	7.10	7.10
7	6.92	6.92	6.92	6.92	6.92	6.92
8	6.76	6.76	6.76	6.76	6.76	6.76
9	6.60	6.60	6.60	6.60	6.60	6.60
10	6.45	6.45	6.45	6.45	6.45	6.45
11	6.31	6.31	6.31	6.31	6.31	6.31
12	6.17	6.17	6.17	6.17	6.17	6.17
13	6.04	6.04	6.04	6.04	6.04	6.04
14	5.91	5.91	5.91	5.91	5.91	5.91
15	5.79	5.79	5.79	5.79	5.79	5.79
16	5.67	5.67	5.67	5.67	5.67	5.67
17	5.56	5.56	5.56	5.56	5.56	5.56
18	5.46	5.46	5.46	5.46	5.46	5.46
19	5.35	5.35	5.35	5.35	5.35	5.35
20	5.25	5.25	5.25	5.25	5.25	5.25

Deck 2

$\mathrm{D.O.}_i$ $\mathrm{D.O.}_o$ (Deck 1) + Recharge

$\Delta\mathrm{D.O.}$ 25% reduction of $\mathrm{D.O.}_i$ (Deck 2)

$\mathrm{D.O.}_o$ $\mathrm{D.O.}_i$ (Deck 2) - $\Delta\mathrm{DO}$ (Deck 2)

Recharge - 10% of $\mathrm{D.O.}_i$ (Deck 1)

Deck 3

$\mathrm{D.O.}_i$ $\mathrm{D.O.}_o$ (Deck 2) + Recharge

$\Delta\mathrm{D.O.}$ 20% reduction of $\mathrm{D.O.}_i$ (Deck 3)

$\mathrm{D.O.}_o$ $\mathrm{D.O.}_i$ (Deck 3) - $\Delta\mathrm{D.O.}$ (Deck 3)

Recharge - 10% of $\mathrm{D.O.}_i$ (Deck 1)

Deck 4

$\mathrm{D.O.}_i$ $\mathrm{D.O.}_o$ (Deck 3) + Recharge

$\Delta\mathrm{D.O.}$ 15% reduction of $\mathrm{D.O.}_i$ (Deck 4)

$\mathrm{D.O.}_o$ $\mathrm{D.O.}_i$ (Deck 4) - $\Delta\mathrm{D.O.}$ (Deck 4)

Recharge - 10% of $\mathrm{D.O.}_i$ (Deck 1)

Deck 5-n

$\mathrm{D.O.}_i$ $\mathrm{D.O.}_o$ (Deck 4) + Recharge

$\Delta\mathrm{D.O.}$ 15% reduction of $\mathrm{D.O.}_i$ (Deck 5)

$\mathrm{D.O.}_o$ $\mathrm{D.O.}_i$ (Deck 5) - $\Delta\mathrm{D.O.}$ (Deck 5)

For each deck, determine the number of fish (take-out size) allowable:

$$\frac{\text{D.O. (mg/hr)}}{\text{SMR per fish (mg/hr)}}$$

Determine the stocking number:

No. allowable of take-out size + expected mortality.

Determine the pounds to be stocked:

$$\frac{\text{input number}}{\text{n/lb. (stocking size)}}$$

LOADING SEQUENCE MULTIPLE REUSE RACEWAYS

		% Sat. (est.)		% Sat. (Act.)
Deck A	in	100		100
		-30	30% DO dec.**	-30
	out	70		70
	recharge	10**		(from Table 8)
Deck B	in	80		78.2
		-20	25% DO dec.	-19.6
	out	60		58.6
	recharge	10		(from Table 8)
Deck C	in	70		69.5
		-14	20% DO dec.	-13.9
	out	56		55.6
	recharge	10		(from Table 8)
Deck D	in	66		68.5
		-9.9	15% DO dec.	-10.3
	out	56.1		58.2
	recharge	10		(from Table 8)
Deck E	in	66.1		69.5
		-9.9	15% DO dec.	-10.4
	out	56.2		59.1
	recharge	10		(from Table 8)
Deck F	in	66.2		70.0
		-9.9	15% DO dec.	-10.5
	out	56.3		59.5

** Minimum fall of 1' between decks

*** For each 1000' >MSL the %ΔDO is Decr. by 3.8%

Table 8. Reaeration values for different weir heights. Values are determined by the saturation of water leaving the previous reuse pond.

Reaeration Tables for Various Weir Heights

Weir Height (feet/cm)

Saturation at Outfall of Upper Reuse Pond	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
	15.2	30.5	45.7	60.9	76.2	91.4	106.7	121.9
98%	.9840	.9855	.9865	.9873	.9879	.9885	.9890	.9894
96%	.9681	.9709	.9729	.9745	.9758	.9770	.9780	.9789
94%	.9521	.9564	.9594	.9618	.9638	.9655	.9670	.9683
92%	.9362	.9419	.9459	.9490	.9517	.9540	.9560	.9577
90%	.9202	.9273	.9323	.9363	.9396	.9425	.9449	.9472
88%	.9042	.9128	.9188	.9236	.9275	.9309	.9339	.9366
86%	.8883	.8982	.9053	.9108	.9155	.9194	.9229	.9260
84%	.8723	.8837	.8917	.8981	.9034	.9079	.9119	.9155
82%	.8563	.8692	.8782	.8854	.8913	.8964	.9009	.9049
80%	.8404	.8546	.8647	.8726	.8792	.8849	.8899	.8943
78%	.8244	.8401	.8512	.8599	.8671	.8734	.8789	.8838
76%	.8085	.8255	.8376	.8471	.8551	.8619	.8679	.8732
74%	.7925	.8110	.8241	.8344	.8430	.8504	.8569	.8626
72%	.7765	.7965	.8106	.8217	.8309	.8389	.8458	.8521
70%	.7606	.7819	.7970	.8089	.8188	.8274	.8348	.8415
68%	.7446	.7674	.7835	.7962	.8068	.8158	.8238	.8309
66%	.7287	.7529	.7700	.7835	.7947	.8043	.8128	.8204
64%	.7127	.7383	.7564	.7707	.7826	.7928	.8018	.8098
62%	.6967	.7238	.7429	.7580	.7705	.7813	.7908	.7992
60%	.6808	.7092	.7294	.7452	.7584	.7698	.7798	.7887
58%	.6648	.6947	.7158	.7325	.7464	.7583	.7688	.7781
56%	.6489	.6802	.7023	.7198	.7343	.7468	.7577	.7675
54%	.6329	.6656	.6888	.7070	.7222	.7353	.7467	.7570
52%	.6169	.6511	.6752	.6943	.7101	.7238	.7357	.7464
50%	.6010	.6366	.6617	.6815	.6981	.7123	.7247	.7358
48%	.5850	.6220	.6482	.6688	.6860	.7007	.7137	.7253
46%	.5690	.6075	.6346	.6561	.6739	.6892	.7027	.7147
44%	.5531	.5929	.6211	.6433	.6618	.6777	.6917	.7041
42%	.5371	.5784	.6076	.6306	.6498	.6662	.6807	.6936
40%	.5212	.5639	.5940	.6179	.6377	.6547	.6697	.6830

Table 9. Percent saturation of water when the partial pressure of dissolved oxygen is 90 mmHg.

Water Temperature °C	Elevation (in feet above msl)					
	0	1000	2000	3000	4000	5000
0	0.5687	0.5909	0.6140	0.6380	0.6619	0.6876
1	0.5692	0.5917	0.6150	0.6388	0.6628	0.6882
2	0.5694	0.5916	0.6151	0.6391	0.6627	0.6888
3	0.5691	0.5915	0.6148	0.6387	0.6626	0.6882
4	0.5698	0.5924	0.6153	0.6396	0.6634	0.6891
5	0.5701	0.5924	0.6159	0.6397	0.6636	0.6900
6	0.5703	0.5927	0.6163	0.6402	0.6642	0.6900
7	0.5705	0.5930	0.6162	0.6407	0.6647	0.6906
8	0.5709	0.5935	0.6168	0.6408	0.6654	0.6912
9	0.5714	0.5941	0.6174	0.6414	0.6660	0.6918
10	0.5718	0.5945	0.6178	0.6418	0.6663	0.6921
11	0.5726	0.5953	0.6186	0.6432	0.6670	0.6934
12	0.5729	0.5956	0.6189	0.6434	0.6677	0.6940
13	0.5736	0.5962	0.6201	0.6446	0.6689	0.6951
14	0.5743	0.5970	0.6208	0.6452	0.6693	0.6961
15	0.5748	0.5975	0.6212	0.6462	0.6709	0.6968
16	0.5751	0.5981	0.6217	0.6465	0.6710	0.6974
17	0.5762	0.5991	0.6226	0.6473	0.6723	0.6985
18	0.5772	0.6000	0.6240	0.6485	0.6732	0.7000
19	0.5771	0.6004	0.6243	0.6485	0.6238	0.7003
20	0.5782	0.6014	0.6250	0.6506	0.6748	0.7019

Estimates of fish numbers varied greatly from the recorded pound inventory values for all raceways (Table 4). We were unable to determine if the specific source of the error was in the method, but think it was due to one or a combination of the three factors:

1) The model was incorrect in that it predicted elevated values of individual oxygen consumption, thereby giving an underestimate of fish numbers when dividing it into the total oxygen consumption. Previous data from another facility indicated that the predictions of fish numbers were correct (+ or - 3%) at 15 C, so it was suspected that problems were inherent with the model as the water temperatures dropped. However, we compared predicted values for oxygen consumption given by our model with those given by Mueller-Fuega et al (1978) and found them to be highly correlated when plotted against each other at all temperatures.

CORRELATION COEFFICIENTS AMONG METHODS
TO ESTIMATE NUMBERS OF FISH IN A RACEWAY POND

	MUELLER-FEUGA	EXPERIMENTAL
Actual	0.99917	0.99902

2) The second source of error may have been inaccurate flow measurements. A sensitivity analysis, performed on all the variables, indicated that a 10% increase in the water inflow measurement will elicit a 10% increase in the predicted fish numbers, while a 10% increase in weight or

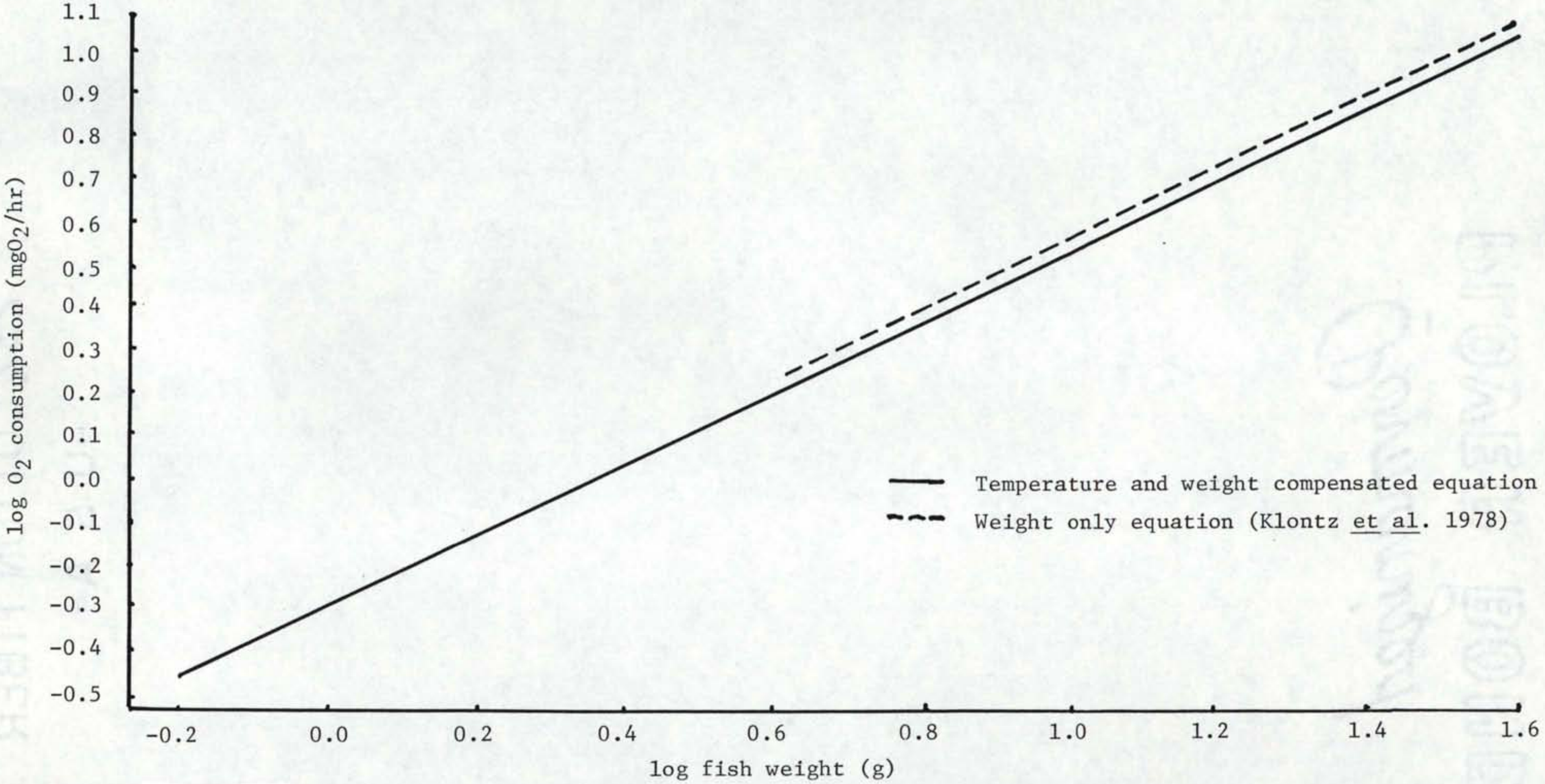

Figure 5. Comparisons of derived oxygen consumption slope with that developed by Klontz *et al.* (1978).

temperature measurements will only affect a 6.0-3.0% change in predicted numbers, respectively. This points out that an inaccurate flow measurement can have a large effect on the model's predictive capability.

3) The third source of error involves the location of water sample removal for dissolved oxygen determination. Incoming water was nearly 100% saturated with oxygen, but as the water moved down the raceway, oxygen was removed by fish respiration shifting the equilibrium and causing oxygen to diffuse into the water at an increased rate. Because the water in the raceways was not agitated, only a small surface layer was reaerated, but it was from this layer that the water samples were removed. The higher concentration of the surface layer may have biased the results by producing a small ΔDO or underestimating the total oxygen consumption.

Other problems concerning the measurement of dissolved oxygen which may or may not have played a part in this study are sampling water from a "dead" area created by the flow pattern, such as above a venturi dam outlet, and the necessity to have a total biomass present in the raceway to remove enough oxygen to permit the ΔDO to be out of the range of variability in Winkler titration (i.e., ΔDO must be = 0.5 mg/l).

To more fully explore the role of dissolved oxygen determination in applying the census-taking model, estimates of what the outfall dissolved oxygen should have been according to the population estimates presented in the hatchery records were calculated (Table 10).

Table 10. Estimates of dissolved oxygen concentrations based upon recorded population size.

	Dissolved Oxygen (mg/l)		
Pond No.	inflow	outfall (recorded)	outfall (calculated)
1	8.2	7.0	6.75
2	10.1	6.7	5.88
3	12.4	11.8	11.60
4	12.3	10.9	10.95
5	12.0	11.3	10.80
6	12.4	11.3	11.50
7	12.2	11.8	11.69
8	12.1	11.3	11.28
9	12.2	11.1	11.26
10	11.8	10.7	10.92

From these data, there are several valid observations. The dissolved oxygen determinations are insufficiently precise for the model. The Winkler method has an accuracy of 10^{-1}; however, the data indicate that a 10^{-2} accuracy is required because the values are expanded 3600-fold to generate the mg O_2 per hour in the system.

SUMMARY

This study provides preliminary evidence that the concepts of using oxygen consumption models to predict population size in raceways systems and to predict carrying capacities in multiple reuse raceways systems are sound. This study should be re-evaluated when the oxygen determination problems are solved.

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16. Abstract

Models for oxygen consumption by rainbow trout were developed and preliminarily tested under laboratory and field conditions. The major factor leading to inaccuracies in estimating population numbers was determined to be the sensitivity of measuring the dissolved oxygen entering and leaving the systems. Further studies are planned.

17a. Descriptors

*Oxygen consumption, Aquaculture, Rainbow trout

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