

WATER QUALITY AND WATER EXCHANGE TIME
IN CAGED CHANNEL CATFISH CULTURE

By

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PREFACE

Commercial culture of food fish in America has expanded rapidly in the past decade. Once restricted largely to other nations, fish farming is now a respected form of American agriculture. In Oklahoma, small scale production of catfish in cages suspended in farm ponds is becoming common place. It is my hope that this research will both benefit small fish producers in this state and have applications to large scale fish production. My thanks are extended to Langston University, the Oklahoma Cooperative Fish and Wildlife Research Unit and the Department of Agriculture for their support of this research.

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CHAPTER I

INTRODUCTION

Channel catfish (Ictalurus punctatus) have been grown as a food fish in many different culture systems and under many different levels of intensity (Bardach et. al., 1972; Dupree and Huner, 1984; Stickney, 1979). Most often culture has been undertaken in specially designed culture ponds but the culture of fish in cages suspended in the water has been proposed as a means of growing fish in farm ponds where harvesting by seine is not possible due to irregular pond bottoms (Collins, 1978; Williams et. al., 1984). While harvesting is facilitated by cage culture, there are disadvantages associated with the high densities of fish (up to 500 fish/m³) (Schmittou, 1969a): parasites or diseases are easily transmitted and waste products may build up rapidly. Two aspects of this second problem form the basis of this dissertation.

This study attempts to develop regression models for caged catfish growth rates and feed conversion ratios based upon interior cage water quality and to develop a practical method of measuring water exchange rate through cages. Much effort has been spent in studying the effects of water quality on fish, particularly in determining acute toxicities of various water quality factors, but

little work has been done on the chronic effect of these factors on fish in culture systems. Chronic exposure to low water quality conditions lowers resistance to disease, decreases growth rate and increases the weight of feed required to produce a given amount of fish weight gain (feed conversion ratio or FCR). Much of the work has dealt with the effect of these factors acting singly but usually several factors act simultaneously to produce a cumulative effect. Disease epizootics in cultured fish offer a good example of this complex interaction.

Epizootics are often the result of water quality stressors which have weakened the immunological response of the fish rather than the virulence of the disease organism (Meyer, 1979; Wedemeyer and Wood, 1974; Walters and Plumb, 1980).

The first area of research is an exploratory effort to determine aggregate water quality effects upon catfish growth. This effort differs from most scientific research in that it does not involve the testing of a hypothesis. Instead, it attempts to discover statistically significant associations which might indicate cause-effect relationships. The first objective is to determine possible synergistic aggregate water quality effects upon catfish which could be further investigated in the laboratory. The second objective is to provide a measure of the effects of aggregate water quality on catfish production which could be of use to fish farm managers.

Much work has been done on the effects of water quality variables upon fish growth, however, with the

exception of a few studies (Shesterin et al, 1979; Lloyd and Herbert, 1960; Thurston, 1979) only individual water quality variable effects have been investigated. In addition, earlier work had been conducted under laboratory conditions and laboratory data are often markedly different from data collected in the field (Doudoroff, 1957; Giesy and Allred, 1985). Fish in culture systems are simultaneously exposed to a wide variety of water quality variables, each of which has the potential for chronic or acute harm. Fish experience water quality as an aggregate; it is therefore appropriate that the aggregate effect of water quality on fish be investigated in addition to single parameter laboratory studies.

The second area of research, involves developing a method for measuring water exchange rates in open ponds and cages. The objective is to provide a basis for the design of fish culture cages in which water exchange is rapid, thereby ensuring good water quality. Designing fish culture cages that minimize water exchange time first requires the development of a means to measure low velocity water movement. In addition to cage design, it might be useful for fish culturists to have a means of measuring low velocity flow rates in different pond locations to determine the best site within a water body to locate cages. The measurement of changes in water velocity due to fish culture cages alone and together with fish are secondary objectives.

Two factors act to determine water exchange time in fish culture cages: the hydraulic efficiency of the cage and the movement of water due to fish motion. Hydraulic efficiency, the ratio of the kinetic energy of water leaving the cage to the kinetic energy of water entering the cage, should depend upon configuration of the cage (shape and dimensions), orientation of the cage to the direction of water movement and the diameter of the mesh with which the cage is constructed. These factors can all be controlled to varying extents by the fish culturist in an attempt to minimize exchange time. The magnitude of the reduction in water velocity due to the cage is unknown. The presence of fish in the cage probably acts to speed up water exchange rates under conditions of low velocity water movement (< 10 cm/sec) but no information is available to substantiate this hypothesis.

CHAPTER II

LITERATURE REVIEW

Water Quality and Temperature Related Effects on Fish

Fish in most culture systems in developed nations are provided with an nutritionally complete diet. In ponds, the high level of nutrient input, in the form of feed, results in progressively more eutrophic conditions. The degradation of water quality associated with eutrophic conditions is widely believed to be the most significant cause of reduced in fish growth (Boyd, 1979).

Dissolved Oxygen

In static water aquaculture, dissolved oxygen (DO) is generally the most critical water quality factor. Vertebrates are dependent upon oxygen as a part of metabolic pathways involving energy transformations. Most tissues depend upon a constant supply of oxygen from the blood to supply the requirements of oxidative phosphorylation.

Low DO levels are the major factor associated with catfish kills under culture conditions (Boyd et al, 1979b; Boyd et al, 1975). Even when low DO levels do not result in mortalities, chronic effects can significantly reduce

production of channel catfish. Growth of channel catfish is reduced when DO levels remain continuously below 4 to 5 mg/l (Andrews et al, 1973). Carlson et al (1980) showed that when juvenile channel catfish (2.9 g) were subjected to constant DO levels less than 3.5 mg/l, growth rate was significantly lower than when levels exceeded 3.5 mg/l. However, if DO levels fluctuated so that the fish were only exposed to levels below 3.5 mg/l in the morning, then growth rates were not reduced. Feed consumption of both juvenile and adult channel catfish has also been shown to be reduced when DO levels fall below 5.0 mg/l, but feeding does not cease until levels drop below 3.0 mg/l (Randolph and Clemens, 1976).

Dissolved oxygen levels in ponds undergo a diurnal pattern in which levels rise during daylight hours until dusk and then fall during nighttime hours until they reach the lowest point at dawn. The major factor associated with extreme levels of DO in fish culture ponds are the intense phytoplankton blooms which result from the fertilizing influence of fish culture (Swingle, 1968; Boyd et al, 1975). Photosynthetic production of oxygen by phytoplankton is the leading source of DO in fish culture ponds and is dependent upon the level of solar radiation (Boyd and Hollerman, 1982). Large fish kills often occur during periods of cloudy warm weather when phytoplankton undergo high levels of respiration.

Low DO levels in fish ponds can usually be traced to high feeding rates: critically low levels usually do not

occur if less than 30 pounds of feed/acre/day are dispensed (Swingle, 1968). Commercial fish farmers, however, feed at rates well in excess of this level and so must use emergency aeration periodically to avoid mass mortality. Emergency aeration is usually employed only after DO levels drop below 2.0 to 3.0 mg/l (Boyd and Tucker, 1979). As a result of emergency aeration only at these levels and other management practices, catfish are often exposed to chronically low DO levels. This situation could be alleviated by continuous aeration but the costs of such a practice probably exceed the level of additional return (Hollerman and Boyd, 1980).

Ammonia

In intensive aquaculture, once adequate oxygen levels are maintained, ammonia is the water quality parameter which most often limits production (Colt and Armstrong, 1981). Ammonia is a metabolic by-product of protein assimilation by fish and is excreted through the gills by means of simple diffusion (Smith, 1929). Because gills do not actively transport ammonia, the process can be reversed so that high environmental levels of ammonia diffuse back into the bloodstream. Ammonia is believed to exert its toxic effect via the blood with effects including swelling and reduced numbers of red blood cells, tissue damage, and reduced resistance to disease (Flis, 1968; Soderburg, 1984).

Ammonia occurs in a combination of un-ionized and ionized forms. A combination of both forms is called total ammonia nitrogen (TAN). Toxic levels of TAN range from 0.6 to 2.0 mg/l (Dupree and Huner, 1984). Un-ionized ammonia (NH₃) is widely held to be the most toxic component of total ammonia (Colt and Armstrong, 1981). The 96 hour LD50 for channel catfish is 3.10 mg NH₃/l (Ruffier et al, 1980). Chronic effects of nitrogenous waste products on channel catfish include reduced growth and gill hyperplasia. Colt and Tchobanoglous (1978) reported a linear decrease in the growth of juvenile channel catfish (1-2 g) over a range of from 0.048 to 0.989 mg NH₃/l. Soderburg (1984) observed gill lesions in year 2 channel catfish cultured in static water, when average daily maximum levels of NH₃ were 0.063 mg/l or overall daily maximum levels of NH₃ were 0.020 mg/l.

Total ammonia nitrogen levels generally remain constant throughout the day, although the proportion of NH₃ will change reaching a maximum in the afternoon when levels of carbon dioxide are low and pH is high. Ammonia may either be taken up by phytoplankton or undergo microbial oxidation to nitrite and nitrate. Phytoplankton die-offs can result in rapid increases in the levels of ammonia experienced by fish as cell walls break down releasing metabolites (Boyd et al, 1975).

Temperature

Fish are poikilotherms and are subject to marked changes in growth and physiological processes as a function of temperature. In general, fish do not grow until a minimum temperature is exceeded, then growth increases with increasing temperature until a point is reached where further temperature increases result in decreased growth rates. The rate of increase in oxygen consumption with a 10°C rise in temperature (Q_{10}) is a commonly used measure of an organisms response to temperature. Channel catfish have a Q_{10} of 1.9 to 2.3 (Andrews and Matsuda, 1975). This level is typical for fish, indicating that channel catfish are neither more or less affected by temperature changes than other poikilotherms.

Temperature extremes capable of killing fish seldom occur in fish culture situations but suboptimal conditions are common. Temperature tolerances are hard to pinpoint for fish because they can become acclimated depending on their temperature history (Doudoroff, 1957). The optimum temperature for growth and FCR of juvenile channel catfish (4 g) is 30°C (Andrews and Stickney, 1972). Dupree and Huner (1984) state that the temperature range between 23.9°C and 29.4°C is optimum for the growth of year 2 channel catfish in ponds.

Other Factors Affecting Channel Catfish

Unfortunately, factors other than water quality also affect fish growth, feed conversion ratio and survival. Among these "other factors" are body size, crowding, behavior and pheromones.

Body Size

Fish are known to exhibit different rates of growth as a function of growth stage (Brown, 1957). This differential growth is strongly associated with sexual maturity and catfish in culture systems are nearing sexual maturity at the time of harvest. Lovell (1984a) reported that under open pond culture conditions, channel catfish of different sizes (46, 153, and 550 g initial weight) exhibited consistent differences in percentage growth (688% to 169%, respectively) and in feed conversion ratio (1.43 to 2.16, respectively). Smaller fish consumed more feed, had faster rates of growth, and converted feed more efficiently than larger fish.

Crowding

Certain aquatic organisms such as crustaceans adapt poorly to crowded conditions while other species, such as channel catfish adapt readily (Stickney, 1979). In fact, when caged channel catfish are not crowded sufficiently (< 100 fish/m³) aggressive behavior and poor production

are the result (Konikoff and Lewis, 1974). There are, however, upper limits (400 fish/m³) beyond which caged channel catfish production declines (Schmittou, 1969a). Whether the decline is due to behavioral factors or low water quality associated with high fish density or a combination of the two is not known. The ratio of fish density to inner cage water surface area may be of importance both in the ability of all individuals to reach the water surface during feeding and during periods of low DO. During periods of low oxygen, catfish rely upon the oxygen-rich surface diffusion layer.

There is little evidence to support the assertion that high density alone is a significant stressor of cultured catfish, but Murray (1980) observed that stocking density affected red blood cell morphology. Fish held in 20,000 liter raceways (25 minute turnover time) at high densities (433.0 kg/m³) had 3.5% smaller and 0.6% rounder red blood cells than fish held at low densities (0.18 kg/m³). If under these conditions the total number of red blood cells remained the same but the average surface area was reduced, then these fish could be more susceptible to the harmful effects of low DO levels than those grown at lower densities. Klinger et al (1983) observed physiological and hematological changes in large (565 to 740 g) channel catfish at high stocking densities. Catfish of this size, are not generally used in fish culture because they adapt poorly to confinement. Water quality was not monitored in either of these studies.

Size Hierarchies

A wide variety of fish have been shown to exhibit differential rates of growth when individuals of different sizes are cultured together. The growth rate of individual Salmo trutta fry in high density situations appears to be a function of the number of larger fry. Conversely, in low density situations, growth is related to the relative number of larger and smaller individuals (Brown, 1957). One explanation for differential growth is that larger fish exert dominance over smaller ones, obtaining a disproportionate share of feed. Alternately, smaller fish may not efficiently process feed in the presence of larger fish. Knable (1972) observed that in the presence of large channel catfish, small catfish do not change the volume of feed consumed. There appears to be some size limits within which differential growth does not occur. Konikoff and Lewis (1974) found that caged catfish did not undergo differential growth when the initial coefficient of variation (CV) of weight ranged from 0.10 to 0.90. Apparently those cage populations with low initial CV tended to experience increased CV at harvest while the opposite was true for populations with high initial CV. These last two studies suggest that size hierarchies have only minor effects on growth rate when initial length variation is within the limits that are generally recommended for catfish fingerlings which are to be stocked in cages (1/2 inch larger or smaller than an average length of 5-8 inches) (Beem, 1986).

Alarm Substance

Channel catfish have specialized cells in the epidermis which release a pheromone when damaged (Yoakim and Grizzle, 1981; Love, 1970). This alarm substance or schreckstoff is thought to function as a warning signal for conspecifics when one individual is injured by a predator. The behavior induced is a fright response (Smith, 1982). Normally, caged fish would not sustain injuries that would lead to the release of such substances, but periodic sampling of fish for experimental purposes could subject the entire population of a cage to this additional stressor. The effects of this substance upon growth related factors is unknown.

Aggregate Effects On Fish

Multiple factors will affect fish in either an additive, synergistic or antagonistic fashion. When the effect is additive, the aggregate effect is equal to the sum of the individual effects. When a synergistic interaction between factors occurs, the aggregate effect will be greater than the sum of the individual effects. The opposite is true for antagonistic interactions. With regard to aggregate water quality factors, the effects of metal ions provide the best understood examples of synergism and antagonism. Southgate (1948) reports that certain metal cations are synergistic while others are antagonistic in their toxicity to fish. Dissolved

minerals can also interact with toxic compounds to reduce their apparent toxicity either antagonistically or through chemical reaction (Doudoroff, 1957). It should be noted that for true synergism or antagonism to occur there must not be any appreciable chemical reaction between the compounds in question.

Relatively little is known of the aggregate effects of other water quality factors on fish. The effect of oxygen level on growth is known to depend upon fish body size and temperature. Young fish are especially susceptible to low DO levels because they use more oxygen per unit body weight than do large fish (Fry, 1971; Holeton, 1980). At a water temperature of 30°C, a 50 g channel catfish consumes 0.80 mg oxygen/g body weight/hour in comparison to 0.45 mg oxygen/g body weight/hour for a 500 g fish (Andrews and Matsuda, 1975). The relationship between fish weight, water temperature and oxygen consumption has been developed by Andrews and Matsuda (1975):

$$\begin{aligned} \log_{10} \text{ oxygen consumption in mg oxygen/g of fish/hour} = \\ -0.999 - 0.000957W + 0.0000006W^2 + 0.0327T \\ - 0.0000087T^2 + 0.0000003WT \end{aligned}$$

where W = average weight in grams and T = temperature in °C . Although DO levels are recognized as important, the relationship of fluctuating DO regimes to growth and feed conversion of channel catfish is not well understood in either cage or open pond culture systems (Boyd, 1979).

The effects of ammonia are intimately involved with those of several other factors. Laboratory methods only allow the direct measurement of total ammonia nitrogen (TAN) which consists of un-ionized ammonia (NH_3) and ionized ammonia (NH_4). The concentration of these two compounds is determined by the use of equilibrium equations involving temperature and pH levels (Emerson et al, 1975). Ammonia is likely to interact with other water quality variables resulting in a more pronounced effect upon fish. For instance, the gill hyperplasia produced by ammonia may exacerbate the effects of low DO by reducing the gill surface area available for gas exchange. During periods of low DO, more water is forced across the gills so that the exposure to environmental levels of TAN is greater. In addition, if oxygen intake is reduced, the rate of carbon dioxide excretion will fall raising the pH at the gill surface and so shift the equilibrium to favor the more toxic NH_3 form (Lloyd and Herbert, 1960).

The toxic effect of ammonia on rainbow trout (Salmo gairdneri) and fathead minnows (Pimephales promelas) has been shown to be enhanced by temperature, independent of its role in the equilibrium relationship between NH_3 and NH_4 (Thurston, 1979). Low DO levels enhance the acute toxicity of ammonia for a variety of warm water fishes when it drops below one-half to one-third of saturation levels, (Merkens and Downing, 1957; Vamos and Tasnadi, 1967).

In addition to the combined effects of different environmental factors, the ability of fish to acclimate to water quality factors should also be considered. Thurston (1979) offers a broad review of the literature which indicates that both warm and cold water species are less susceptible to mortality from high ammonia levels when they have previously been exposed to low levels of ammonia.

Exchange Rate in Fish Culture Cages

When fish are stocked at high densities, the likelihood of chronic or acute harm to them increases sharply, due to the direct effect of toxic metabolites and low levels of DO (Tucker et al., 1974; Smitherman and Boyd, 1974). In cage culture systems, fish are dependent upon water flow through the cage to remove metabolic wastes and supply DO. It is possible that inner cage water quality is worse than that of the outer cage water and that the difference is biologically significant. There is some inferential support for this hypothesis. Schmittou (1969a) demonstrated the importance of water exchange rates by arranging 16 rectangular catfish culture cages in a 4 by 4 block pattern. The inner cages were thus blocked from receiving water from the open pond and presumably experienced slower exchange rates than those on the outside. Fish in inner cages grew 18% slower than those in the outer cages. If exchange time varies based

upon cage location in the pond, then it would be advantageous to place them so as to insure the maximum rate of water exchange between the pond and cage. At present, no method has been developed to measure water exchange time in cages.

The measurement of water exchange time is basically a matter of determining inner cage water velocity. Little work has been done on current flow in standing water but the standard method of determining velocity in streams involves the use of a propeller-type current meters (Lind, 1979). However, these instruments are ineffective at velocities of less than 0.1 m/sec and so are not suited to work in lentic situations. Dean (1983) discusses several types of sophisticated flowmeters that could perhaps be modified for the measurement of water velocity in ponds. The major disadvantages of these instruments are their high cost and limited history of applications to situations other than water flow through pipes. None of these instruments appear applicable to the measurement of water flow when that water contains large numbers of fish, as in the case of a fish culture cage.

Hydrologists have explored several innovative techniques for measuring discharge rates of rivers with shifting bottoms (Rhodda et al, 1976; Herschy, 1976). In the ultrasound method, sound pulses are transmitted from opposite sides of a river in offset positions. The difference in the time required for sound pulses to travel in the upstream and downstream directions is directly

proportional to the average velocity of the water. This method might be applicable to open pond situations, but the direction of flow must be determined first, and a cage could interfere with the propagation and reception of sound impulses. Another possible method to measure flow is the electromagnetic method, where measurements are taken of the electromagnetic force generated by the movement of water. The magnitude of the force generated is proportional to the velocity of the water. In a pond, however, the extremely small electromagnetic force generated by low velocity water movement would likely be masked by interfering electrical potentials.

The use of tracers is the method that seems to have the greatest possibility for application in fish culture cages. Hydrologists use two different tracer methods to determine stream discharges. In the constant injection method, a tracer is continuously injected by means of a specialized apparatus and the change in concentration of the tracer at a point downstream is monitored over time. In the "slug" method, a volume of tracer is injected instantaneously and the change in concentration is monitored over time at a point downstream. A modification of the slug method was used by Boyd and Martinson (1984) as a means of determining the relative effectiveness of aerators in mixing waters in fish culture ponds. Of the four possible approaches discussed above, the slug method appears to be the most appropriate choice for measuring exchange rate in cages, since it requires only inexpensive

equipment, and does little harm to the study site, provided that a non-toxic tracer is used.

Before the use of tracers in measuring water velocity can be understood, it is first necessary to appreciate the two physical processes responsible for the movement of water and dissolved substances through fish culture cages. The first of these is advection and the second is diffusion. Advection is the movement of solutes by flowing water at average velocities (Freeze, 1979). Diffusion is the mixing of molecules resulting from random motion. Of the two processes, advection is the most important means by which solutes are dispersed in bodies of standing water (Chapra and Reckhow, 1983). Even though advective currents in ponds are of much lower magnitude than those occurring in rivers and large water bodies, they usually have an effect far in excess of that produced by diffusion.

Although diffusion has a lesser effect than advection, much more is known about the properties of the former. The rate at which a solute diffuses in water is dependent both upon temperature and the nature of the solute itself (Chapra and Reckhow, 1983). Diffusion coefficients (D) have been empirically determined for different solutes at different temperatures by taking the limit as distance (x) and time (t) approach 0:

$$D = \frac{dx^2}{2dt} \quad (1)$$

When the solute initially occurs at the origin ($x = 0, t = 0$), concentration at a given position x at a given subsequent time t is given by:

$$C_{x,t} = M_p e^{-x^2/(4Dt)} / 2(\pi Dt)^{1/2} \quad (2)$$

where M_p is the total mass of the particles per cross sectional area of the interface (mass per area).

Advective currents always occur in water bodies, and therefore diffusion and advection work simultaneously to transport solutes. The effect of these two processes can be visualized as a series of bell shaped curves shifting in the direction of the current and simultaneously widening. The net transfer of mass per unit area of the interface per unit time due to both processes is expressed as:

$$J = UC - D \frac{dc}{dx} \quad (3)$$

where J is the total flux due to advection and diffusion, U is velocity, C is concentration, D is the diffusion coefficient of the solute and x is distance from point of injection. Equation (2) can be substituted into equation (3) which can then be rearranged to yield the rate of change in concentration with respect to time:

$$\frac{dC}{dt} = D \frac{d^2c}{dx^2} - U \frac{dc}{dx} \quad (4)$$

In the special case where a slug of solute is instantaneously released into a one dimensional channel equation (4) can be modified and the concentration of the tracer at any location and time calculated:

$$C_{x,t} = (M_p / 2(\pi Dt))^{1/2} e^{-((x-Ut)^2 / 4Dt)} \quad (5)$$

This model offers a good compromise between accuracy and practicality for the purpose of understanding the processes involved in the displacement of metabolic waste laden water out of fish culture cages and its replacement by fresh water. As in any model, certain simplifying assumptions are present. These include constant velocity, lack of turbulence, and instantaneous dispersal of the tracer into the interface plane. It appears reasonable to assume that water movement in ponds will be constant in direction and velocity over short periods of time, but accepting the other two assumptions is more difficult. The second and third assumptions deal with the movement of tracer molecules by diffusion. It is apparent that upon injection, a tracer will not immediately diffuse laterally to some defined limit and then cease diffusing. Therefore, the second assumption would be invalid if the rate of tracer movement due to diffusion is significant in comparison to that due to advection. However, because the proportion of solute movement due to diffusion is usually insignificant in comparison to that due to advection (Chapra and Reckhow, 1983), it is reasonable to overlook

the complications arising from changes in the interface area due to diffusion.

CHAPTER III

WATER QUALITY RELATED EFFECTS ON CAGED CHANNEL CATFISH

Materials and Methods

Experimental Ponds

Four similar 1.0 acre ponds located 7.5 miles west of Stillwater, Oklahoma and immediately below the dam of Lake Carl Blackwell were used as study sites. These ponds had flat gently sloping bottoms with average depths of 3 and 6 feet at the shallow and deep ends, respectively. Water was supplied by means of gravity flow through pipes from Lake Carl Blackwell. Two cages were located in each pond at opposite ends of a T-shaped dock, separated by a distance of 5 m. Each pond was stocked with grass carp (Ctenopharyngodon idella) at a rate of approximately 10 fish/acre to prevent excessive aquatic vegetation growth (Bennett, 1974).

Fish Culture Cages

The cages used were cylindrical and had a volume of 1 m³. The cage material was Vexar with a mesh diameter of 1/2 inch. Permanently installed Tygon tubing, which extended to shore, allowed removal of water samples

without disturbance of fish and any resultant change in water quality variables. This tubing was painted to exclude light and to discourage algal growth on inner surfaces.

Protocol

Each cage was stocked with 300 channel catfish fingerlings (approximately 6 inches in length). Fish that died during the first 2 weeks were replaced. A 36% protein floating catfish feed was dispensed using one automatic and one demand feeder fitted cage in each pond. Fish in the automatic feeder fitted cages received 3% of their total estimated body weight in feed once daily. The amount of feed dispensed was measured for each cage.

The study period extended from June to September and was divided into two week periods. In the four experimental ponds, a subsample of 50 or more fish from each cage was removed, weighed en mass, and returned to the cage, at the beginning of each period. Instantaneous growth rate (Medawar, 1945) and feed conversion ratio were then calculated for each period and cage. The amount of feed dispensed was measured at 3-4 day intervals over the entire period.

Water quality variables within cages were measured twice weekly (Appendix A). Samples were collected at a depth of 60 cm from within each cage as well as at a point midway between both cages. A peristaltic pump was used to collect samples via permanently installed tubing. This

type of pump eliminated contamination of samples with atmospheric gases and did not subject samples to a partial vacuum which might have allowed gases to come out of solution.

Temperature and dissolved oxygen levels were determined on site by inserting a thermometer and DO probe into an overflowing bottle fed by the peristaltic pump. Plastic bottles were used to collect water samples which were then placed on ice and transported to the lab for further analysis. Total ammonia nitrogen (TAN) and pH were determined by Hach spectrophotometric methods. The un-ionized ammonia (NH_3) content of the sample was determined using the equation given by Emerson (1975). Standard solutions of known NH_4 and pH concentration were analyzed along with the unknown solutions. The DO meter was periodically calibrated using a Hach modified Winkler procedure. Coefficients of variation for TAN and pH were 6.2% and 0.4%, respectively. The average deviation of the DO meter was 6.6%. Secchi disc readings were taken midway between cages at weekly intervals to provide an estimate of phytoplankton abundance. A visual estimate of the percentage of pond surface covered by aquatic vegetation was made weekly.

A number of different water quality variables were measured in each pond at a point midway between cages at monthly intervals (Appendix B), in order to better describe overall water quality conditions. Table I compares the range of values for water quality variables

TABLE I

COMPARISON OF SELECTED WATER QUALITY VARIABLES
FROM EXPERIMENTAL PONDS WITH LITERATURE
VALUES FOR CATFISH PRODUCTION PONDS

Variable	Experimental Ponds	Literature Value	Citation	Note
Secchi Disc	30.9 - 112.5 cm	40.0 - 80.0 cm 25.0 - 160.0 cm	Hollerman & Boyd, 1980 Boyd et al, 1979	
Chemical O2 Demand	23.0 - 49.0 mg/l	39.8 mg/l 17.0 - 78.0 mg/l	Hollerman & Boyd, 1985 Boyd et al, 1979	
Orthophosphate	0.0 - 0.053 mg/l	0.001 - 0.007 mg/l	Boyd et al, 1979	
Total Nitrate/ Nitrite	0.0 - 0.16 mg/l	0.011 0.00 - 0.05	Hollerman & Boyd, 1985 Hollerman & Boyd, 1980	nitrite nitrite
Total Ammonia Nitrogen	0.23 - 0.98 mg/l	0.08 - 0.80 mg/l 0.05 - 1.05 mg/l	Hollerman & Boyd, 1980 Boyd et al, 1979	
Dawn Dissolved Oxygen	3.1 - 6.7 mg/l	2.5 - 7.8 0.8 - 6.4 1.9 - 8.3 2.7 - 5.8	Hollerman & Boyd, 1985 Hollerman & Boyd, 1980 Boyd et al, 1979 Boyd et al, 1979	
Temperature	24.3 - 29.3	21.3 - 33.4	Boyd et al, 1979	June-Oct.
Total Hardness	115-162 mg/l CaCO3	12.3 - 55.5	Arce & Boyd, 1980	Alabama
Total Alkalinity	112-149 mg/l CaCO3	11.6 - 51.1	Arce & Boyd, 1980	Alabama

in the ponds with those reported for catfish production ponds in the literature. These variables included orthophosphate, nitrate/nitrite, conductivity, chemical oxygen demand, total hardness and total alkalinity. As with the other variables previously mentioned, samples were obtained at a depth of 60 cm. Most analyses were conducted using Hach spectrophotometric techniques.

Sampling Effect

The extent to which growth is affected by removing and returning 50 or more catfish per cage at two week intervals is a matter of concern. One way of determining this effect would be to establish a control treatment where fish are not disturbed by sampling. However, because of the high level of variability in water quality between different fish culture ponds (Shell, 1983) it would probably be necessary to include one or more control cages per pond. Given the limited carrying capacity of the ponds available for this study (2 cages per pond) and the need to obtain as much data as possible for regression analysis, it was decided that an alternative means of estimating sampling effect would be used.

The difference in feed consumption of fish in cages with demand feeders during the period of a few days before and a few days after sampling disturbance was compared using a sign test. The lengths of the before and after periods were matched as closely as the data allowed and ranged from 3 to 6 days. Feed consumption was expressed

as the ratio of feed consumed per day to total fish weight at the start of each 3 to 6 day period. Total fish weight at the beginning of the pre-sampling period was determined by interpolation while weight at the beginning of the post-sampling period was available from the sampling itself.

The null hypothesis that before and after sampling feed consumption were equal was rejected at the $P = 0.05$ level but accepted at the $P = 0.04$ level ($N = 24$). Average change in feed consumption was small: -0.12% of body weight, while the average rate of feed consumption for these before and after periods was 2.99% of body weight. A larger reduction in feed consumption following biweekly sampling would be a good indication that sampling had significantly affected growth. Because no such large reduction was observed, it is apparent that sampling effect was slight and can be disregarded.

Statistical Analysis

Data quantifying growth rate and feed conversion ratios were analyzed in four phases. First, a factorial design was used to determine if pond, period or feeder type had a significant effect upon growth rate or feed conversion ratio. This approach was necessary in order to determine if any of these three factors should be used in subsequently developed multiple regression models.

Second, linear regressions were performed based upon single predictors: mean temperature, mean fish weight at

the start of each period, mean morning DO, mean morning un-ionized ammonia, and mean secchi disc readings. This was done to obtain a measure of the predictive power of these basic parameters.

Third, multiple regression models based upon the five predictors used in the first phase plus TAN were developed using the stepwise routine of the Statistical Analysis System (SAS).

Fourth, multiple regression models were developed based upon complex predictors. A wide variety of predictors were tested using the stepwise routine. These predictors included transformations of average values for each period, extreme values of variables, average value of variables in the previous period, differences between present period and past period average values, and interactions between two different predictors based upon all of the previously mentioned complex predictors. Any predictor which was significant at the $P = 0.10$ level or greater was included in the models developed.

Results

Production Parameters

Daily growth rates for fish ranged from 2.50 to 3.30 g/day (Table II) while feed conversion ranged from 1.19 to 2.16 (Table III). Survival of fish ranged from 87.0% to 100.0% (Table IV). The lower rates of survival in ponds 2 and 4 were attributed to a phytoplankton die-off related period of low DO and a disease epizootic, respectively.

TABLE II

MEAN DAILY GROWTH OF CATFISH (g/day)

<u>Pond</u>	<u>Automatic Feeder Cage</u>	<u>Demand Feeder Cage</u>
1	3.30	2.62
2	2.50	2.84
3	2.77	3.10
4	2.95	3.03

TABLE III

AVERAGE FEED CONVERSION RATIO* OF CATFISH

<u>Pond</u>	<u>Automatic Feeder Cage</u>	<u>Demand Feeder Cage</u>
1	1.47	1.42
2	1.60	1.71
3	1.32	2.16
4	1.55	1.19

* Weight of feed dispensed per unit of fish weight gain

TABLE IV

SURVIVAL OF CATFISH (PERCENTAGE)

<u>Pond</u>	<u>Automatic Feeder Cage</u>	<u>Demand Feeder Cage</u>
1	99.0	100.0
2*	95.7	97.3
3	96.7	100.0
4**	93.7	87.0

* Automatic feeder and demand feeder cages in this pond experienced 29.3% and 30.7% mortality, respectively when morning DO levels were estimated to have been as low as 2.0 ppm during period 1. Cages were restocked to bring cage population back to 300 fish.

** During periods 2 and 3, 4.0% and 8.0% of the cage populations died, respectively. Freshly dead fish were observed to have large necrotic gill lesions, consistent with a heavy gill parasite infection.

Factorial Design

Under the factorial design, pond and feeder type were not shown to significantly affect growth. Period, however, did significantly affect the dependent variables of growth rate and feed conversion ratio ($P > F = 0.0001$). Period is simply a measure of time in 2 week intervals and so is of little biological meaning. Therefore, a correlation analysis was done to identify biologically meaningful alternatives. Four independent variables were found to be significantly correlated with period: fish weight ($P < 0.0001$), mean DO ($P = 0.0012$), secchi disc reading ($P = 0.0399$) and mean un-ionized ammonia ($P =$

0.0495). On the basis of the highly significant correlation between weight and period, the former was chosen to replace period as a predictor. Since growth curves are seldom linear, several powers of weight were used iteratively to identify the best fit between weight and period. Weight squared yielded the best r^2 value (0.98) when regressed against period ($P < 0.0001$), and so was included in all multiple regression models.

Univariate Models

Growth rate regressed significantly against three simple predictors: Temperature, fish weight, and oxygen (Table V). Of these three predictors, fish weight was the most significant and accounted for a large proportion of the variation in growth rate. The three regression models were:

$$\text{Growth Rate} = -2.1608 + 0.1660T$$

$$\text{Growth Rate} = 3.1856 - 0.00463W$$

$$\text{Growth Rate} = 1.3844 + 0.2193DO$$

Where T = average water temperature (C), W = average fish weight(g) at the start of each period, and DO = average morning dissolved oxygen level (mg/l).

TABLE V

LINEAR REGRESSIONS OF GROWTH RATE AGAINST
FIVE INDIVIDUAL PREDICTORS

<u>Predictor</u>	<u>P>F</u>	<u>r²</u>
Temperature	0.0379	0.0774
Weight	0.0001	0.3473
Oxygen	0.0396	0.0761
NH3	0.5867	0.0055
Secchi	0.8611	0.0006

Feed conversion ratio (FCR) also regressed significantly against temperature, fish weight and DO (Table VI). Fish weight was the most significant predictor although DO was a much better predictor of feed conversion ratio than it was of growth rate. The three regression models were:

$$\text{FCR} = 5.1191 - 0.1258T$$

$$\text{FCR} = 1.0282 + 0.003075W$$

$$\text{FCR} = 2.6624 - 0.2341\text{DO}$$

Where T = average water temperature (°C), W = average fish weight (g) at the start of each period and DO = average morning dissolved oxygen level (mg/l).

TABLE VI

LINEAR REGRESSIONS OF FEED CONVERSION RATIO
AGAINST FIVE INDIVIDUAL PREDICTORS

<u>Predictor</u>	<u>P>F</u>	<u>r²</u>
Temperature	0.0316	0.0842
Weight	0.0001	0.2899
Oxygen	0.0022	0.1634
NH3	0.8180	0.0010
Secchi	0.4604	0.0103

Multiple Regression Models Using
Simple Predictors

When the five simple variables were used in the stepwise routine as predictors of growth rate only weight squared appeared in the model ($P > F = 0.0001$, $r^2 = 0.3547$):

$$\text{Growth Rate} = 2.8415 - 0.00001144W^2$$

where W = fish weight. In the case of feed conversion ratio, weight squared and morning DO were included in the model ($P > F = 0.0001$, $R^2 = 0.3562$):

$$\text{FCR} = 1.9908 - 0.1479\text{DO} + 0.00000648W^2$$

where DO = average morning dissolved oxygen and W = fish weight.

Multiple Regression Models Using
Complex Predictors

The multiple regression model developed for growth rate using complex predictors was:

$$\begin{aligned} & \text{Average daily weight gain} \\ & = 2.78 - 0.0000105W^2 + 0.0191 (\sin(\text{DO2}) - \sin(\text{DO1}))T \end{aligned}$$

where W is average fish weight (g), DO1 is average morning dissolved oxygen (mg/liter) in the previous period, DO2 is average morning dissolved oxygen (mg/liter) in the current period, T is average morning water temperature in the current period, and sine is expressed in radians.

Individual probability levels for the predictors were $P = 0.0001$ and $P = 0.0015$, respectively. Overall R^2 value for the model was 0.476 with a probability level of $P > 0.0001$.

The multiple regression model developed for feed conversion ratio using complex predictors was:

$$\begin{aligned} \text{FCR} = & 2.08 + 0.00000723W^2 - 4.63 ((\text{DO2}-\text{DO1})/\text{N2}) \\ & - 0.146(\text{DO1}) - 0.00889(\text{N1}) \end{aligned}$$

where W is average fish weight (g), DO1 is average morning dissolved oxygen (mg/liter) in the previous period, DO2 is average morning dissolved oxygen (mg/liter) in the current period, N2 is average morning un-ionized ammonia (micrograms/liter) in the current period, and N1 is average morning un-ionized ammonia (micrograms/liter) in

the previous period. Individual probability levels for the predictors were $P = 0.0001$, $P = 0.0010$, $P = 0.0654$ and $P = 0.0655$, respectively. The overall R^2 value for the model was 0.457 with a probability level of $P > 0.0001$.

Conclusions and Recommendations

The models developed provide the first insight into the relationship between catfish production parameters and water quality under the naturally fluctuating cycles of water quality found in fish culture ponds. The relatively low R^2 values of the models developed in my study indicate that more than half of the causes of variation in the dependent variables is unexplained. One possibility is that important independent variables were not measured or were measured inadequately. Ideally, I would have liked to have measured actual daily growth and feed conversion ratios as dependent variables to daily water quality measurements. The sampling regime used was a compromise between the need to minimize disturbance of fish and to obtain data for periods short enough to reflect immediate water quality effects. However, the protocol may have caused me to fail to measure extreme water quality conditions of short duration. In addition, high ammonia or low DO levels, at critical periods could have had effects on the fish out of proportion to their contribution to average values for a given period. For example, there appears to be a threshold at the level of 60% DO saturation, below which catfish exhibit metabolic dependence (Andrews et al, 1973).

Most of the regression models developed are readily understood, but the multiple regression model for growth rate using complex predictors requires further explanation. The biological significance of the sine function is not immediately apparent. The range of average dissolved oxygen levels experienced during this study (3.0 to 6.7 mg/l) corresponds approximately to the interval from π to 2π which is from 3.14 to 6.28 radians. Over this range, the minimum value of the sine curve occurs at 4.71. This level of dissolved oxygen is approximately equal to the 60% saturation level below which catfish exhibit metabolic dependence upon oxygen (Andrews et al, 1973). This similarity lends support to the argument that the 60% saturation level of dissolved oxygen may be of importance in the management of fish production ponds. Care should be taken in attempting to interpret the possible effects of dissolved oxygen level on growth rate with respect to the sine function: the distribution of dissolved oxygen values in this study (mean = 4.60 mg/l, SD = 0.94) may be unusually amenable to regression against growth rate using this function. Prediction models for growth rate in culture systems where the mean dissolved oxygen level differs significantly from 4.71 mg/l may not benefit from the inclusion of the sine function.

The approach taken in this study has been oriented toward management practices, at the expense of determining actual causal relationships. For instance, the use of

instantaneous growth rate as a dependent variable oversimplifies the complex phenomenon of growth. A more theoretical study would have considered rates of change in such factors as the ratio of body muscle to total weight and gonadosomatic index, instead of merely changes in total weight. The use of weight as a predictor because it was highly correlated with time, can also be criticized as overlooking several other factors which also are highly time related. Factors such as endocrine levels probably act to cause biorhythms in fish that are independent of environmental factors (Love, 1970). The problem with the more theoretical approach is that the factors involved would often be beyond the control of the fish farm manager.

Future Laboratory Studies

The models suggest that both synergism and acclimation effects are present. Dissolved oxygen appears to be interacting with temperature and levels of un-ionized ammonia to exert larger effects upon fish production than the sum of the individual effects would predict. The measure of DO level involved is the difference between average DO level for the present period and that of the past period. This trend in DO level reflects the magnitude of the difference between a naturally occurring 2 week period of acclimation and the subsequent 2 week "experimental" period. A two-way factorial laboratory experiment could be used to determine

if synergism and acclimation are real factors affecting the growth of catfish. Factor combinations including the trend in DO levels at different constant NH₃ levels or the trend in DO levels at different constant temperatures would be evaluated in separate experiments. In such an experiment an F value for interaction larger than the F value for main effects would indicate synergism. Ideally, in this experiment both independent variables would undergo diurnal fluctuations typical of those found under field conditions.

Fish Farm Management

The models developed should be applicable to a variety of geographical locations and fish culture regimes. The growth rates, feed conversion ratios and water quality experienced during this study were typical of those found in extensive (< 30 pounds of feed dispensed/acre/day) caged catfish culture (DaSilva, 1983; Williams, 1982). The similarities of extensive open pond and caged catfish culture are great enough that I believe the models developed can be applied in either case. Certainly there is a much greater degree of similarity between open pond and cage culture than there is between open pond culture and laboratory toxicity studies. Cage culture differs from open pond culture in two important aspects: water quality conditions in cages may be worse than those in open ponds, due to high fish density and restrictions in water exchange rate, and behavioral

factors associated with high fish density. No significant differences were found in water quality between inner and outer cage water quality during the course of this study.

Caution should be exercised, however, when attempting to apply the models I have developed to intensive (> 50 pounds of feed dispensed/acre/day) open pond culture situations. Under heavier feeding regimes, significant differences in water quality develop: DO often drops below critical levels and harmful levels of substances such as nitrite and hydrogen sulfide may be present (Boyd 1979; Tucker et al, 1979; Cole and Boyd, 1986).

The models suggest that catfish should be harvested at the smallest size possible, if the only objectives are to obtain maximum growth rate and feed conversion efficiency. There are, of course, other factors which determine the optimum harvest size of fish. The size of fingerlings stocked, time of stocking and length of growing season all act to determine the range of sizes through which fish will grow. In this region it is recommended that 6-8 inch fingerlings be stocked in April to Mid-May so that a harvestable size (3/4 pound) fish be obtained by September (Williams et al, 1984). The choice of a smaller stocking size or later stocking date would lead to larger growth rate and greater feed conversion efficiency yet this approach would be economically undesirable because of fish weight loss and the expense of holding catfish overwinter (Beem et al, 1986; Lovell and Sirikul, 1974). Environmental and economic constraints in

Oklahoma dictate that harvest of year 2 channel catfish must occur in the fall but producers in areas with longer growing seasons could take advantage of the superior growth characteristics of smaller size fish by stocking smaller fingerlings.

Refinements of the models of water quality effects upon catfish that I have developed may become future tools of fish farm managers. Equations that relate the total effect of major water quality variables to growth rate and feed conversion ratio should allow the manager to convert water quality data into a meaningful measure of production. At present, most fish farm managers employ emergency aeration only when DO levels fall to a point where a major fish kill is threatened or problems are suspected from ammonia levels. The overall picture is one of educated guesswork when the survival of up to 40 tons of catfish in a pond may depend on correct management decisions. Under these conditions, the relatively simple models based on temperature, DO and ammonia levels developed in this study could greatly aid managers in avoiding losses.

A second category of models which predict growth rates based on daily fluctuations of water quality under different management regimes would also greatly aid managers in attempting to achieve optimum production systems. Due to factors such as weather and the instability of phytoplankton populations (Boyd et al, 1975), it will probably never be totally feasible to

predict daily fluctuations in water quality, but models which predict the probability of chronically or acutely harmful levels of water quality variables are possible. Such models together with models quantifying the aggregate effects of water quality factors should provide a basis for quantifying the ratio of risk to return for different stocking, feeding, pond draining and aeration practices. The models developed in this study should serve as a basis for these more sophisticated efforts.

CHAPTER IV

WATER EXCHANGE TIME IN FISH CULTURE CAGES

Materials and Methods

Study Site Conditions

A 1.0 acre pond located 7.5 miles west of Stillwater, Oklahoma and immediately below the dam of Lake Carl Blackwell was used as the study site. The pond was rectangular in shape having a length approximately equal to twice the width and a flat sloping bottom, 3 and 6 feet in depth at the shallow and deep ends, respectively. The dam of Lake Carl Blackwell and oak woodland surrounding the pond on the other sides, provided a significant amount of shelter from wind. The pond was unstratified with an average temperature of 28°C .

Water velocity was measured according to the injection method protocol, at three different sites. The three sites were adjacent to a dock located in the deep end of the pond and were separated from each other by approximately 2 m. Prevalent wind direction was used to estimate the direction of advective flow in the pond so that site locations along the dock could be selected to minimize interference.

Protocol

Two methods of measuring low velocity water flow were evaluated under field conditions. The injection method involved injecting a tracer solution into the center of a 1 m³ volume cylindrical cage constructed of 1/2 inch Vexar mesh. Tracer solution was prepared by dissolving 100 g of NaCl in 4 liters of pond water and then poured into the cage at a depth of 60 cm using a funnel consisting of a length of 1 1/2 inch internal diameter Polyvinylchloride pipe and a 4 liter plastic bottle with the bottom removed. About 40 seconds was required to inject the tracer. If it was poured at a faster rate, air became entrapped and caused turbulence as bubbles rose. After injection, the funnel apparatus was removed and 5 water samples withdrawn from the point of injection at 60 second intervals by means of a peristaltic pump. A conductivity meter was used to determine the conductivity of each sample as well as baseline levels. The bag method differed from the injection method in that the entire mass of water contained in an 11.6 liter model of the larger cage, also built of 1/2 inch Vexar mesh, was used as the tracer. A plastic bag was placed around the cage and 100 g of NaCl dissolved within it. At time equal to 0 sec, the bag was removed and 5 samples were withdrawn at 60 sec intervals using a syringe.

The effect of cages and fish on inner cage water velocity was evaluated by measuring water velocity with

the injection method under three different conditions: the open pond, an empty 1 m³ volume cylindrical cage (diameter = 1 m, depth = 1.33 m) and an identical cage containing approximately 250 fish with an average weight of 340 g.

The bag method was not used to measure water movement in empty 1 m³ cages or in cages containing fish because of the difficulty in manipulating a bag of the size required. Instead, the smaller cage model was used to obtain these estimates.

Calculation of Velocity and Water Exchange Time

From these data velocity can be calculated using the following rearranged form of equation (5) where $x=0$:

$$U = \frac{1}{t} \left(4Dt \ln \left(\frac{M_p}{2(\pi Dt)^{1/2} (C_{x,t})} \right) \right)^{1/2} \quad (6)$$

where U = velocity of flow (cm/sec), x = distance from injection point, t = time from injection (sec), D = diffusion coefficient of NaCl (cm²/sec), M_p = total mass of solute particles in the slug of tracer (mg) divided by the cross sectional area of the interface (cm²) through which it is moving and $C_{x,t}$ = tracer concentration (mg/cm³) at time t and distance x . A linear regression of concentration against conductivity was used to determine concentration. The diffusion coefficient (D) was obtained by calculating the mean of coefficients for Na⁺ and Cl⁻ (Li and Gregory, 1974). At 0°C the mean coefficient is

8.2×10^{-6} cm²/sec, at 18°C it is 14.2×10^{-6} cm²/sec, and at 25°C, 16.8×10^{-6} cm²/sec . Estimated values at other temperatures were developed through interpolation.

In order to calculate M_p , it is necessary to determine the cross sectional area of the interface plane between the tracer and the advective current. In the ideal case where no turbulence is involved in the injection of the tracer and the injection is instantaneous, the injected tracer can be visualized as a sphere which is displaced by advection and expands due to diffusion. The interface plane is equal to the maximum cross sectional area of the sphere and can be calculated by using the following equation:

$$A_t = \pi(1 + Dt) \left(\frac{3V}{4\pi} \right)^{2/3} \quad (7)$$

where A = area of tracer interface plane (cm²), T = time (sec), V = volume of tracer (cm³), D = diffusion coefficient (cm²/sec)

However, since there is turbulence associated with injection and about 40 seconds is required to inject the tracer, the bag method, where the interface area is simply the vertical cross sectional area of the cage, provides a more accurate measurement of water velocity.

In either method M_p is calculated as:

$$M_p = N / (A_t - MA_t) \quad (8)$$

where N = mass of NaCl (mg) in tracer solution, A = area of tracer interface (cm^2), and M = decimal proportion of cage material occupied by mesh. In this study $M = 0.271$.

It is necessary to forgo calculations of velocity after the first measurement of conductivity has fallen to near-baseline levels. If this approach is not used, equation (6) will yield measurements that are lower than actual values since there is no longer any measureable level of tracer in the sample. In this study, near-baseline was defined as being within 20 micromhos of baseline.

Once U is determined for each sample time, a mean value is taken as the measure of velocity for that trial. The time required to completely exchange inner and outer cage water is then calculated by the following equation:

$$E = W/U \quad (9)$$

where E = exchange time (seconds), W = average length of the path that water follows as it moves through the cage (cm) and U = inner cage water velocity (cm/sec).

Results

Water velocities determined by the injection and bag methods are presented in Table VII and Table VIII, respectively. Inner cage water velocity in the cage containing channel catfish was significantly greater ($P = 0.008$) than it was under the other two conditions

according to the Kruskal-Wallis test. In all trials, in the cage containing fish, the measurement of conductivity at time zero approximated baseline levels in the pond. Therefore, the tabular values for this condition represent only minimum possible velocities. No significant differences were detected between water velocity in open pond and empty cage conditions using the injection method. However, with the bag method, there was a 20.9% cage related reduction in velocity. The Mann-Whitney test showed that the difference was significant at the $P = 0.09$ level.

TABLE VII

MEAN WATER VELOCITIES (cm/sec) AS DETERMINED
BY THE INJECTION METHOD FOR
THREE CONDITIONS

<u>Trial</u>	<u>Open Pond</u>	<u>Empty Cage*</u>	<u>Cage with Catfish**</u>
1	0.003264	0.002093	0.006650@
2	0.002082	0.003378	0.005964
3	0.003058	0.002399	0.006031
4	0.002386	0.003485	0.006336
5	0.002464	0.003073	0.004602
mean	0.002651	0.002886	0.005913
CV@@	18.6%	21.2%	13.3%

* 1 m³ volume cylindrical cage (1 m diameter, 1.33 m depth) constructed of 1/2 inch Vexar mesh.

** identical cage stocked with approximately 250 channel catfish weighing an average of 350 g each.

@ all values in this column represent minimum possible velocities

@@ Coefficient of variation

TABLE VIII

MEAN WATER VELOCITIES (cm/sec) AS
DETERMINED BY THE BAG METHOD
FOR TWO CONDITIONS

<u>Trial</u>	<u>Open Pond</u>	<u>Empty Cage*</u>
1	0.00758	0.00556
2	0.00793	0.00798
3	0.00792	0.00639
4	0.01204	0.00798
5	0.00800	0.00646
mean	0.00869	0.00687
CV**	21.6%	15.6%

* 11.6 l volume cylindrical cage (22 cm diameter, 30.5 cm depth) constructed of 1/2 inch Vexar mesh.

** Coefficient of variation

Conclusions and Recommendations

Measurements with the injection and bag methods had low coefficients of variation, a portion of which can be attributed to real differences in water velocity over time. Clarification of the real precision of both methods could be accomplished in tanks where low constant water

velocities can be maintained. An ultrasound flow meter might be used to obtain a more accurate measure of "true" water velocity and thereby provide the basis for a measurement of accuracy.

It appears that the movement of fish within the cage greatly speeds up the exchange of inner and outer cage water. The water exchange time in cages containing fish could not be accurately determined with the injection method; the motion of the fish flushed the tracer rapidly from the cage. It might be possible to obtain accurate measurements of velocity in cages containing fish by using a constant injection technique instead of the slug technique (Rhodda et al, 1976; Herschy, 1966).

Since the methods used were not suitable for the measurement of water velocity in cages containing fish, a cage DO demand budget was used to obtain an estimate of the magnitude of the effect of fish motion on speeding water exchange. I developed a budget based upon literature values for channel catfish oxygen consumption, as follows. Consider the case of a 1 m³ cylindrical cage stocked with 300 channel catfish, whose average weight is 500 g, at a temperature of 30°C. Andrews and Matsuda (1975) report that a 500 g channel catfish at 30°C requires 0.45 mg oxygen/g body weight/hour. This value is equivalent to 0.0625 mg oxygen/fish/sec. In the case of 300 fish of this weight, the total DO demand for all fish in the cage is 18.75 mg oxygen/cage/sec. The fish are confined in a 1000 liter volume cage, but their own volume

displaces some water so that less than 1000 liter of water is in the cage. The specific gravity of fish is approximately equal to that of water and 1 liter of water weighs approximately 1 kg. The total weight of fish is 150 kg so 150 liters of water is displaced leaving 850 liters of water in the cage. Dividing the total DO demand by the volume of water available to the fish yields the demand for DO in units of mg oxygen/l/sec:

$$\begin{aligned} & 18.75 \text{ mg oxygen/cage/sec} \times 1 \text{ cage}/850 \text{ l} \\ & = 0.02206 \text{ mg oxygen/l/sec} \end{aligned}$$

Water exchange time must at least be rapid enough that water flows through the cage before all the DO is consumed. If we assume that water quality conditions in the pond are optimal with DO at the saturation level of 7.53 mg oxygen/l (Boyd, 1979), then:

$$\begin{aligned} & \text{DO demand (mg oxygen/l/sec)} \times \text{water exchange time (sec)} \\ & = 7.53 \text{ mg oxygen/l} \end{aligned}$$

Under the conditions described, estimated maximum exchange time would be 5.7 minutes, a decrease in the open pond exchange time measured in this study by a factor of 81.5 times. In the case of 50 g catfish, the estimated maximum exchange time is 37.1 minutes, a decrease by a factor of 12.5 times over open pond rates measured in this study. Admittedly, the above calculations simplify or over look a number of factors, but inclusion of such factors should have resulted in even larger decreases in water exchange time.

These results suggest that caged fish mortalities during periods of low pond DO may not only be attributable to lack of oxygen. Fish motion appears necessary to promote the exchange of low DO inner cage water with high DO outer cage water. To maintain high inner cage DO, fish probably become more active as pond DO levels drop. Obviously a threshold exists beyond which aerobic respiration can not support high levels of activity. Under the resulting anaerobic respiration, the lactic acid build-up has a number of effects (Parker et al, 1959; Black et al, 1966) that could contribute to the mortality of caged fish. Prolonged anaerobic respiration would result in fish reaching a point where they are unable to continue to swim rapidly. In the last stages of oxygen deprivation, fish attempt to obtain oxygen from the thin surface diffusion layer but are finally unable to swim to the surface. These data would explain the fact that catfish in cages begin dying at DO levels of approximately 2.0 mg/l, while fish in open pond conditions survive. I have also observed that under low DO levels, smaller fish in cages die sooner than larger fish. Greater susceptibility of small fish to low DO may not be simply due to their higher oxygen requirements, but also to their greater sensitivity to lactic acid or lower capacity for prolonged anaerobic respiration.

Speaking in practical terms, the data presented above suggest that fish culturists should be concerned with maximizing the efficiency with which cages allow fish

motion to speed water exchange rather than attempting to promote the flow of open pond currents through cages. The simplest means of minimizing exchange time is to construct cages with the largest diameter mesh which will still retain the fish and to select a mesh type which has a small proportion of area occupied by mesh material.

In addition, new cage mesh designs may aid in minimizing exchange time. I have observed that caged catfish swim in a circular pattern and always in the same direction. If the pattern of fish induced flow out of the cage is tangential to the perimeter of the cage, then water exchange might be speeded up by the use of a special cage mesh designed to minimize the resistance to tangential flow. The holes in such a mesh would have internal walls which were not parallel to the radial axis, as is standard, but instead parallel to the tangential flow.

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APPENDIXES

APPENDIX A

MEAN UN-IONIZED AMMONIA, DISSOLVED
OXYGEN AND TEMPERATURE
VALUES BY PERIOD

TABLE IX
MEAN MORNING UN-IONIZED AMMONIA* OF POND WATERS**

<u>Pond</u>	<u>Period</u>							
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>
1	34	32	41	37	30	33	33	28
2	42	65	13	21	9	18	28	14
3	14	13	8	11	13	10	17	9
4	16	16	14	20	11	11	22	9

* Expressed in micrograms/liter

** Average of samples collected from both cages
at 60 cm depth at intervals of 3-4 days

TABLE X
MEAN MORNING DISSOLVED OXYGEN LEVELS
(mg/liter of O₂) OF POND WATERS*

<u>Pond</u>	<u>Period</u>							
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>
1	6.7	5.1	4.5	4.5	4.5	5.0	4.1	4.8
2	5.3	4.1	3.1	4.3	3.7	4.4	3.6	4.5
3	6.2	4.3	3.5	4.1	3.9	3.5	3.3	3.6
4	6.2	4.7	5.8	6.0	5.5	5.5	5.4	4.5

* Average of samples collected from both cages
at 60 cm depth at intervals of 3-4 days

TABLE XI
MEAN MORNING TEMPERATURE OF POND WATERS*

<u>Pond</u>	<u>Period</u>							
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>
1	26.5	26.8	28.1	29.3	28.3	27.9	27.5	24.7
2	25.7	26.1	27.8	29.1	28.2	28.0	27.4	24.3
3	26.3	26.8	28.2	29.0	28.4	28.0	27.8	24.5
4	26.6	26.9	28.2	29.3	28.6	28.1	27.9	24.8

* Average of samples collected from both cages
at 60 cm depth at intervals of 3-4 days

APPENDIX B

MEAN MONTHLY WATER QUALITY VALUES

TABLE XII

MEAN SECCHI DISC READINGS (cm) TAKEN MIDWAY
BETWEEN CAGES DURING MID-MORNING*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	77.1	57.4	49.5	62.4	61.0	18
2	112.5	71.0	50.1	59.2	71.1	18
3	58.5	35.8	33.4	30.9	35.6	18
4	75.5	82.9	90.1	86.2	84.2	18

* All values represent phytoplankton predominated turbidity.

TABLE XIII

PERCENTAGE OF POND SURFACE AREA COVERED
BY AQUATIC VEGETATION*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	0.0	0.0	0.0	0.0	0.0	10
2	40.0	7.0	3.3	0.0	12.6	10
3	0.0	0.0	0.0	0.0	0.0	10
4	5.0	7.5	4.3	5.0	5.5	10

* These values were determined by visual estimation.

TABLE XIV
TOTAL HARDNESS (mg/liter of CaCO₃)
OF POND WATERS*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	---	146	152	157	152	3
2	---	115	141	158	138	3
3	---	153	155	162	157	3
4	---	130	136	135	134	3

* Samples taken at 60 cm depth midway between cages.
Samples were obtained mid-morning.

TABLE XV
TOTAL ALKALINITY (mg/liter of CaCO₃)
OF POND WATERS*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	---	140	140	142	141	3
2	---	112	133	149	131	3
3	---	135	138	141	138	3
4	---	122	120	122	121	3

* Samples taken at 60 cm depth midway between cages.
No phenolphthalein alkalinity was present in any
samples.
Samples were obtained mid-morning.

TABLE XVI
 CHEMICAL OXYGEN DEMAND (mg/liter of O₂)
 OF POND WATERS*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	---	49	28	---	39	2
2	---	45	37	---	41	2
3	---	48	34	---	41	2
4	---	40	23	---	32	2

* Samples taken at 60 cm depth midway between cages

TABLE XVII
 CONDUCTIVITY (micromhos/cm) OF POND WATERS*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	660	720	800	855	759	4
2	650	670	790	895	751	4
3	810	790	800	875	819	4
4	750	720	750	780	750	4

* Samples taken at 60 cm depth midway between cages

TABLE XVIII
 ORTHOPHOSPHATE CONTENT (mg/l PO₄)
 OF POND WATERS*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	0.010	0.010	0.000	0.053	0.018	4
2	0.013	0.010	0.000	0.027	0.013	4
3	0.013	0.013	0.000	0.017	0.011	4
4	0.008	0.017	0.020	0.027	0.018	4

* Samples taken at 60 cm depth midway between cages

TABLE XIX
 TOTAL NITRATE AND NITRITE CONCENTRATION (mg/liter)
 OF POND WATERS*

<u>Pond</u>	<u>Jul</u>	<u>Aug</u>	<u>Sep</u>	<u>Oct</u>	<u>Mean</u>	<u>N</u>
1	0.06	0.08	0.00	0.16	0.08	4
2	0.05	0.06	0.00	0.08	0.05	4
3	0.03	0.04	0.00	0.05	0.03	4
4	0.05	0.08	0.06	0.08	0.07	4

* Samples taken at 60 cm depth midway between cages

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