IV. WATER QUALITY

INTRODUCTION

Aquacultural ecosystems, including all of those involving cage fish culture, are composed of physical, chemical and biological factors that interact individually and collectively to influence culture performance. Water is a primary component of all aquacultural ecosystems; therefore, each characteristic of the water is a water quality variable. Although all of the impacting variables are important, only those that normally cause fish stress or otherwise limit performance in some way are of concern to the practical aquaculturist. An understanding of the key variables, how they relate to fish production and how they may be managed to control the aquacultural environment are essential to the aquaculturist. Some of the key water quality variables and their management are discussed in the following paragraphs under physical, chemical and biological factors as they generally behave within aquacultural ecosystems, and as they relate generally to fish culture in ponds and specifically to fish culture in cages suspended in ponds, reservoirs and lakes.

PHYSICAL FACTORS

Temperature

Pure water weighs 1.0000 kg/L at 4° C, about 0.9999 kg/L at both 1° and 7° C, and 0.9965 kg/L at 27° C. This is a direct result of its density, which decreases above and below 4° C. Because of this phenomenon, standing bodies of water tend to thermally stratify during warm seasons, with the warmest water nearest the surface.

The heat capacity of water is greater than for any other natural substance. Therefore, a lake or large body of water must absorb relatively large quantities of heat to increase its temperature. Water temperatures in such environments will lag behind the larger changes in air temperatures. For example, in a daily cycle air temperature may fluctuate 10^{o} C while lake water temperature will fluctuate only 1° C at 50 cm and remain unchanged at 150 cm depth.

Thermal conductivity of water is very low. Heat gain in a lake from the sun is partly absorbed and conducted, but the effective heat distribution is from surface agitation and to a limited extent from convection currents. Convection heat distribution in standing waters occurs primarily with: 1) night time cooling and sinking of surface water; 2) flow entry of colder water from an external source; 3) seasonal cooling of surface water; 4) alternation of cloudy and clear skies; 5) alternation of surface agitation, e.g. by wind and aerators, and calm; 6) advent of cold rain, and 7) cooling of surface water by evaporation.

Thermal (density) stratification will likely occur during the culture period in all standing waters with depths ≥1.5 m if sunlight penetration depth is less than water depth. Stratification occurs as three distinct and separate strata of uniformly warm upper (epilimnion) and uniformly cold lower (hypolimnion) waters separated by a narrow cool transition stratum (metalimnion or thermocline). Stratification develops when heat intake at the surface leads to the formation of a vertical temperature gradient within which the thermal resistance becomes too great for the existing winds to continue mixing the whole water mass. Circulation then becomes increasingly confined to the epilimnion. Stability of stratification is the amount of energy required to break up the thermal strata by mixing the entire volume of water to a relatively uniform temperature. Stability of stratification varies with many factors including depth (e.g. shallow ponds of usually less than 2.0 m are less stable than deep lakes, annual seasons (e.g. rainy weather and cooling temperatures tend to destabilize stratification) and other factors. Fish ponds may regularly stratify and destratify on a daily basis or they may remain stratified throughout an entire culture season. Destratification through overturns in aquacultural ecosystems is usually caused by cooling air temperatures and convection, strong winds, cold rains or mechanical aeration. Low dissolved oxygen syndrome (LODOS) is a likely condition when an aquacultural ecosystem becomes destratified after more than a few days of stratification.

Temperature in ponds and cages is an independent environmental factor over which the culturist has limited control. However, pond stratification can be prevented or broken up with mechanical aerators or water circulators. Destratifying a pond can improve production by directly improving water quality conditions, reducing the risk of low dissolved oxygen and other water quality problems resulting from overturns, and generally providing a less stressful culture environment.

Light and Photoperiod

Daylight, and especially direct sunlight, affects caged fish behavior and production performance by apparently causing stress to the confined fish. Light entering cages should be controlled. Opaque partial or complete covers are recommended to reduce direct sunlight and visibility of moving images above the cage.

The affect of photoperiod on production performance of caged fish is unknown. Caged common carp at about 45° N latitude in various locations of Heilongjiang, China, have been observed over years to consume more feed and grow proportionately faster with extended photoperiods of up to 14 to 16 hours.

Sound

Unnatural and loud sounds affect fish behavior, and sound-induced fright stress may significantly reduce production performance. Such sounds should be avoided in all aquacultural environments, but especially where fish are confined in cages or under handling conditions.

Dissolved oxygen and Low Dissolved Oxygen Syndrome

Oxygen naturally enters standing open waters (ponds, lakes and reservoirs) primarily through oxygen-releasing photosynthesis (about 90-95%), secondarily by diffusion from the air (most effective when aided by surface agitation), and by incoming water. Oxygen exits aquacultural standing waters primarily through plankton respiration, secondarily by fish respiration and by respiration of bottom microorganisms and diffusion. Biochemical oxygen demand (BOD) in fishponds with intensive feeding varies greatly but may be assumed to be about 0.4 to 0.6 mg/l/hr. Oxygen diffuses out of standing open waters only when the surface waters are supersaturated. Oxygen solubility in water is inversely related to water temperature, atmospheric pressure and salinity (Table IV-1).

Table IV-1. Dissolved oxygen (DO) saturation at different temperatures, altitudes and water salinities.

Temp. (°C)	DO (mg/L) in freshwater/altitude			DO (mg/L) in saltwater (ppt salt)		
	0 m	500 m	1000 m	5 ppt	20 ppt	35 ppt
15	9.8	9.2	8.6	9.8	8.9	8.1
20	8.8	8.3	7.7	8.8	8.1	7.4
25	8.1	7.6	7.1	8.0	7.4	6.8
30	7.5	7.1	6.6	7.3	6.8	6.2

Dissolved oxygen (DO) concentrations vary greatly with standing water depths, and usually correspond closely with thermal stratification. Thermally stratified waters may be void of oxygen in the lower (hypolimnion) stratum where oxygen may be consumed but not produced, and be supersaturated with oxygen in the upper (epilimnion) stratum where photosynthesis is active.

Low dissolved oxygen syndrome (LODOS) is perhaps the most critical water quality variable in aquaculture. LODOS involves a combination of low dissolved oxygen (DO), increased free carbon dioxide (CO_2), decreased pH, increased nitrite (NO_2^-) and numerous other factors which combined can significantly reduce fish production performance.

LODOS can be brought on by plankton mass death syndrome (plankton die-off) in eutrophic ponds and lakes. Plankton mass death syndrome is a condition where massive quantities of algae (usually scums of blue-green algae) suddenly die. Phytoplankton die-offs usually occur during clear, calm and warm or hot weather. The dead plankton rapidly decompose resulting in LODOS through both decay and greatly reduced photosynthesis. Algal toxins may also be a LODOS factor and/or an independent stressor during mass decay of phytoplankton.

The greater the plant nutrient availability (eutrophication) in standing waters the greater the: 1) density of plankton; 2) oxygen production and supersaturation in the illuminated layer; 3) oxygen consumption at night; 4) magnitude of day-night oxygen fluctuation; 5) stability of chemical stratification; 6) environmental instability; 7) risk of LODOS problems; and 8) risk of environmental stress to the fish.

Carbon dioxide

Solubility of carbon dioxide (CO_2) in water is only about 0.5 mg/l (0.56 and 0.42 mg/l at 20° and 30°C, respectively, in pure water), but CO_2 concentrations in intensively managed aquacultural waters normally fluctuate from 0 to $\geq$20 mg/l "free" CO_2 in a 24-hr cycle. Lowest concentrations of occur during the hours of photosynthesis. CO_2 enters aquacultural waters primarily from within as a waste product of respiration and aerobic decomposition of organic matter. Diffusion of CO_2 into aquacultural waters from the atmosphere is relatively insignificant. CO_2 exits aquacultural waters primarily through photosynthesis, where its availability may even limit photosynthesis. Diffusion of CO_2 from aquacultural waters is relatively insignificant in terms of total volume, but it may be extremely important to respiratory (LODOS) stressed fish "gasping" for oxygen at the water surface. CO_2 is temporarily stored in aquacultural waters as bicarbonate (HCO_3^{-2}) when CO_2 reacts with alkaline earth carbonates:

$$\text{Calcium carbonate } (CaCO_3) + CO_2 + H_2O == Ca(HCO_3)_2 \text{ (calcium bicarbonate)}$$

The above reaction is relatively rapid and reversible with the direction of the reaction based on the amount of CO_2 relative to CO_2 solubility. Concentrations of CO_2 in standing waters are normally highest at dawn, but may be abnormally high during cloudy weather and especially after overturns (destratification of thermally stratified waters) and phytoplankton die-offs.

Pond management options to prevent and control accumulation of undesirable amounts of CO_2, which suppress DO absorption by fish, include: 1) maintaining a minimum total alkalinity of 20 mg/l; 2) preventing "permanent" thermal stratification with mechanical aeration-mixing; 3) adding or flushing water to dilute CO_2 concentration; 4) mechanically aerating-mixing water to facilitate diffusion; and 5) carefully and evenly (vertically and horizontally) adding calcium hydroxide ($Ca(OH)_2$) at a rate of 0.84 mg/l for every 1 mg/l CO_2 above 5 mg/l CO_2 in the pond water. For example, a 23 mg/l CO_2 pond concentration requires 15.1 mg/l $Ca(OH)_2$ to reduce the pond CO_2 concentration to 5 mg/l, i.e. 23 mg/l - 5 mg/l CO_2 = 18 mg/l CO_2 x 0.84 mg $Ca(OH)_2$ = 15.1 mg/l

$Ca(OH)_2$. Excess $Ca(OH)_2$ should not be applied because it may increase pH to toxic levels. Pond, lake and reservoir waters that accumulate even moderate amounts of free CO_2 should probably be avoided as waters for cage fish culture.

CHEMICAL FACTORS

pH and Total Alkalinity

The pH of water indicates whether the water will give a basic or acidic reaction relative to the neutral point of pH 7.0. The pH of aquacultural waters normally fluctuates on a diurnal cycle, primarily influenced by CO_2 concentrations, phytoplankton density and total alkalinity and hardness. At desired total alkalinity and hardness levels between about 20 and 150 mg/l, daily pH values during clear weather normally range from about pH 7.0 ± 0.5 at dawn to about pH 9.0 ± 0.5 in the afternoon. In waters with low alkalinity (<20 mg/l), pH will normally range from potentially fish stressing extremes of about pH 5.7 ± 0.5 at dawn to pH 9.7 ± 0.5 in the afternoon. In waters with high alkalinity but low hardness, afternoon pH values may exceed the maximum fish tolerance level of 11.0.

Waters of low alkalinity (<20 mg/l) are undesirable for aquaculture because: 1) they may be so acidic that fish production performance is negatively effected; 2) phytoplankton production will be limited by inadequate CO_2 and HCO_3^{-2}, tending to cause LODOS and possibly causing plankton die-off; 3) fluctuations in pH and related factors may cause water quality instability leading to fish stress; and 4) extreme pH levels resulting from the low buffering capacity of the water may cause acidic stress conditions in the early morning and alkaline stress conditions in the afternoon.

Aquacultural grade limestone ($CaCO_3$) may be used in low alkaline ponds to raise total alkalinities to about 20 mg/l. Hydrated lime (calcium hydroxide, $Ca(OH)_2$) and burnt lime (calcium oxide, CaO) are faster acting and have higher acid neutralizing values than $CaCO_3$, but they are more expensive and are potentially dangerous to the user (burn eyes and skin) and to the fish (rapid changing and excessively high pH). Liming materials should preferably be broadcast evenly over the pond bottom soil or evenly over the entire water surface. There are no practical means of correcting low alkalinity in open waters.

Ammonia

Total ammonia nitrogen in aquacultural ecosystems is a product of fish protein metabolism and bacterial decomposition of organic matter. Total ammonia nitrogen is the combined measure of the two forms of ammonia nitrogen, unionized ammonia (NH_3) and ammonium ion (NH_4^+).

Unionized ammonia is highly toxic to fish, but NH_4^+ is harmless at levels occurring in aquacultural ecosystems. Equilibrium between NH_3 and NH_4^+ is directly regulated by pH and temperature. The toxic NH_3 form increases with increasing pH and temperature (Table IV-2).

Table IV-2. Percentage of total ammonia nitrogen in the fish-toxic, unionized (NH_3) form at different pH and temperature levels.

	NH_3 (%) / temperature (°C)			
pH	15	20	25	30
7.0	< 1	< 1	< 1	1
8.0	2	3	5	8
9.0	21	29	36	45
10.0	72	80	85	89

Tolerance levels of NH_3 for most cultured fishes are between 0.6 and 2.0 mg/l for short term exposure, but stressing levels are as low as 0.1 to 0.3 mg/l. NH_3 cannot be measured directly; but must be determined from a table after measuring total ammonia nitrogen, pH and temperature (Table IV-2). Total ammonia nitrogen concentrations in aquacultural ecosystems are directly proportional to the feeding rate and quantity of protein in the feed. Stressing levels of NH_3 may commonly occur in highly intensive aquacultures and also in lower level aquacultures following phytoplankton die-offs, but lethal levels are rare. Total ammonia nitrogen may be prevented or controlled in aquacultural ecosystems by: 1) limiting feeding rates; 2) controlling water pH, preventing ranges above about pH 8.0; 3) mechanically aerating-mixing the waters in the afternoon when pH values are the highest (NH_3 is volatile at high pH); and 4) adding or flushing high quality water into the ecosystem.

Nitrite

Nitrite (NO_2^-) in aquacultural ecosystems is a product of biological activity related to decomposition of the protein components of organic matter. NO_2^- is produced from NH_4^+ through an oxidation process primarily by Nitrosomas bacteria and from nitrate (NO_3^-) through a reduction process by anaerobic microorganisms. Nitrite may be stressing to fish at water concentrations as low as 0.1 mg/l, and fish blood may become chocolate colored ("brown blood disease") at NO_2^- concentrations of about 0.5 mg/l as a result of hemoglobin being converted to methemoglobin.

However, the toxicity of NO_2^- depends strongly on water pH, calcium concentration and chloride level.

NO_2^- levels are usually highest in aquacultural ecosystems when DO levels are low, which directly contributes to LODOS stress, especially if "brown blood disease" is involved. The toxicity of NO_2^- is probably related to the concentration of nitrous acid which oxidizes the heme ion of hemoglobin from the ferrous to the ferric state, producing methemoglobin. Methemoglobin is incapable of reversibly combining with oxygen, which can cause respiratory distress because of the reduction of oxygen transport by the blood. NO_2^- toxicity may be prevented or treated by: 1) limiting feeding rates; 2) mechanically aerating-mixing the water during periods of low DO, being careful not to stir up anoxic bottom muds; 3) adding or flushing high quality water; and 4) maintaining above neutral pH ($\geq$7.0) and high calcium hardness and chloride levels. The standard pond water treatment for NO_2^- is to increase the ratio of Cl^- to NO_2^- to 6:1 using common salt (NaCl) by the formula: mg/l Cl^- needed = 6(mg/l NO_2^-) - mg/l Cl^- already present.

Hydrogen sulfide

Hydrogen sulfide (H_2S) is produced from sulfate and other oxidized sulfur compounds by anaerobic bacteria. H_2S in aquacultural ecosystems is common only in some lakes and most coastal ponds where it is usually confined in the organic muds. H_2S solubility in water is low and where present it is usually only in trace quantities. Only the unionized H_2S form is toxic to fish. The percentage of unionized H_2S in water is influenced by pH and temperature (Table IV-3).

Table IV-3. Percentage of fish-toxic, unionized hydrogen sulfide (H_2S) in water at different pH and temperature levels.

	H_2S (%) / temperature (°C)			
pH	15	20	25	30
6.0	93	92	91	90
7.0	58	55	51	47
8.0	12	11	9	8
9.0	1	1	1	1

BIOLOGICAL FACTORS

Fish Feeding and Phytoplankton

Approximately 80 to 85% of nutrients in pelleted feeds used in aquacultural ecosystems are released into the water as fecal matter or metabolized compounds that include phosphate, ammonia and carbon dioxide which promote phytoplankton production. Organic matter produced by phytoplankton photosynthesis exceeds by many times the amount of organic matter from fecal wastes. Metabolism by zooplankton, bacteria and other non-phytoplankton microorganisms may be as high as metabolism by fish. Feed wastes increase directly with feeding rates, and phytoplankton densities increase directly with metabolized feed wastes. As phytoplankton density increases, depth of photosynthesis decreases and BOD increases. These changes result in critical water quality deterioration manifesting itself in early morning LODOS conditions.

At lower feeding levels, the ecosystem is in balance between water quality deterioration resulting from feed wastes and water quality restoration resulting from biological utilization of those same wastes. At higher feeding levels and resulting waste loading, the ecosystem balance breaks down primarily because phytoplankton increases proportionately with the metabolic wastes to the point that its contribution to water quality restoration is offset by its impact on water quality deterioration. Ultimately, feeding rate increase is limited by water quality decrease. Thus nutrition, the second limiting factor to cage fish production, gives way to the first limiting factor, water quality, usually in the form of LODOS. Boyd (1990) states that, "As a general rule, fish production increases linearly with feeding rate while water quality deteriorates exponentially with feeding rate." In new ponds and early in the production cycle in older ponds, low to moderate quantities of feed wastes may actually improve water quality for up to a few weeks.

Management techniques to prevent and control water quality deterioration resulting from feed wastes must be based on limiting the feeding amount to a "safe" level relative to methods (environmental modifications) to counter the direct (toxins) and indirect (phytoplankton density and LODOS) effects of the wastes on water quality. Phytoplankton density and scums in ponds may be reduced with algaecides. Copper sulfate ($CuSO_4$) is the most commonly used algaecide in ponds. Standard application techniques include a concentration of 0.1 mg/l $CuSO_4$ for each 10 mg/l total alkalinity applied as a dilute liquid broadcast evenly over the pond surface, or application in a solid form held in meshed bags suspended at the pond surface where the $CuSO_4$ may gradually dissolve into the water and be dispersed throughout the pond by wind induced water currents. One suspended meshed bag of $CuSO_4$/ha is sufficient. Do not exceed 0.1 mg/l $CuSO_4$ for each 10 mg/l total alkalinity because $CuSO_4$ toxicity is directly related to alkalinity level.

Fish Density

Fish stock density in aquacultural ecosystems is a measure of fish numbers or biomass in some unit of water space; volume of cage, area of pond (standing) water or volume rate of raceway (flowing) water. Contrary to common belief, physical crowding of fish at high density is not a primary limiting factor to production performance. In cages the primary factors limiting production at high fish density are LODOS and metabolic wastes that are indirectly related to fish density and directly related to the quantity and quality of feed required to produce them.

Aggressive behavior and possibly pheromones are known or suspected density-dependent social interactions that affect caged fish. Aggressive, territorial behavior is an observed problem with catfish, carp and tilapia at low densities (e.g. <100 fish/m^3) but not at high densities (e.g. >300 fish/m^3). Pheromone influences on growth and general performance of cultured fish are only vaguely known for ponds and suspected for cages. Pheromone influence may be greater at higher fish densities in cages.