WATER QUALITY CONSIDERATIONS
FOR AQUACULTURE

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Introduction

Fish and other organisms with aquacultural potential live in water, thus, it is no surprise that professional fish culturists state that "Water quality determines to a great extent the success or failure of a fish cultural operation" (Piper et al. 1982). Because water is an essential requirement for fish farming, any properly prepared business plan for aquaculture must describe the quality and quantity of water available for the proposed enterprise. An experienced aquaculturist can judge whether the water is suitable for the proposed enterprise.

The objective of this report is to present a brief overview of a few physical and chemical qualities of water that are of importance to aquaculture—the business of fish farming. Although the quantity of water available is of primary importance, only water quality factors are considered here.

Groundwater and Surface Water Sources

There are two main categories of water supply for aquaculture, groundwater and surface water. Groundwater (also called well water, or spring water) often differs substantially from surface water in many characteristics (Table 1). Groundwater is commonly considered the most desirable water source for aquaculture because, at a given site, it is usually consistent in quantity and quality, and free of toxic pollutants and contamination with predator or parasitic living organisms. Natural springs occur where groundwater emerges from rock stratum containing an aquifer. Because spring water has consistent and desirable temperature characteristics, not to mention the valuable fact that it may not be necessary to pump the water to the raceways, springs are the most common water supply for land based trout and salmon culture (land based as contrast with net pen culture in coastal waters). Idaho's rainbow trout production, the largest U.S. producer of food-size rainbow trout, with 74.6% of the 53.6 million pounds in 1996 (USDA 1996), is based on numerous spring flow from the walls of the Snake River Canyon near Hagerman in southern Idaho. Just one facility, Clear Springs, the largest producer of rainbow trout in the USA, raised 18 million pounds in 1990 (Anonymous 1990).

The temperature and quality of groundwater varies latitudinally and from site to site because of geological characteristics of the aquifer (the bed or layer of earth, gravel, or porous stone that yields water)—old aquifers often have high concentrations of radon, a factor that is seldom considered as a factor in aquaculture. Briny (i.e., salinity > 7 parts per thousand, ppt) groundwaters are widely dispersed in the U.S., and surface waters in the intermountain basin area of Utah, Nevada, and other arid western sites are also saline (e.g., Salt Lake, Utah) or alkaline. In west Texas, large quantities of shallow groundwater are not used for conventional agriculture because they are too saline (> 7 parts per thousand), however, they have been considered an aquaculture potential resource for culture of red drum, an economically popular sport and food fish from the Gulf of Mexico

(Forsberg et al. 1996). Groundwater that is considered to be of impaired quality for human use (i.e., water with high concentrations of magnesium sulfate, which has purgative for humans) may be useful for aquaculture.

Table 1. Generalizations about comparative characteristics of groundwater (well, spring) and surface water supplies for aquaculture (concentrations in mg/L = ppm).

Variable	Ground water	Surface water
Temperature	Varies latitudinally and by depth of well, but constant at same site.	Varies seasonally.
Turbidity (NTU)	Low (clear water)	Variable, usually medium to high from inorganic solids (clay or silt) and/or algae.
Dissolved gases		
Total gas pressure (ÆP)	High (N supersaturation)	Low[1]
Nitrogen (N)	High	Low[1]
Dissolved oxygen (DO)	Low, usually <1 mg/L	Variable, but >5 mg/L
Carbon dioxide ($C0_2$)	High (0-50 mg/L)	Variable, but <5 mg/L
Hydrogen sulfide & methane	Uncommon	In anaerobic hypolimnion of stratified ponds.
pH	Low, typically < 7.0, because of high $C0_2$, small diurnal variation.	Variable (6.5-8.5) large diurnal variation, low before sunrise, highest in mid-day, increased by algae.
Dissolved solids		
TDS (mg/L) (salinity)	Variable, but it can be briny (>1,500 mg/L NaCl).	Variable, usually < 400 mg/L
Phosphorus	Typically much lower than surface sources.	Typically > groundwater, but higher in watershed ponds with row crops or livestock.
Ammonia (TAN)	Low (<1.0)	Variable, may be high (cattle and hog confinement, or manure from dairy farms).
Nitrates	Variable, but high in shallow wells in areas with abundant corn production	Variable, but high in watersheds with abundant corn production.
Alkalinity (measures ability to neutralize acids)[2]	Low in granitic or shale, medium to high in limestone aquifers.	Variable, but higher in watersheds underlain with limestone.

Hardness (chiefly Ca^{++} and Mg^{++} ions).[3]	Variable, but commonly medium to hard (50-250 mg/L) .	Variable, soft to hard.
Soluble iron (Fe^{++}) and manganese (Mn^{++})	Common, quickly oxidized in air (O_2) to insoluble forms (Fe^{+++}, Mn^{+++})	Only in anaerobic hypolimnion of stratified ponds.

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[1] See Boyd (1990a) about occurrence of gas supersaturation in ponds. [2] Determined by titration with a dilute solution of a strong acid (0.022 N H_2S0_4). [3] Determined by titration with EDTA, a chemical that chelates Mg and Ca (formerly titrated with a standard soap solution).

An excellent reference on surface water supplies for aquaculture is Yoo and Boyd (1993). Runoff is obviously related to rainfall, therefore, water supply for watershed ponds is quite seasonal. Water storage is affected by seepage and evaporative losses, which vary in relation to temperature and relative humidity. However, a large watershed pond (lake) may have sufficient storage volume to be suitable for cage culture or as a water supply for aquaculture. Obviously, water quality of watershed ponds is strongly influenced by land use. Watersheds dominated by row crops are typically higher in inorganic suspended solids from soil erosion than groundwater supplies.

Runoff of plant fertilizers (i.e., nitrogen and phosphorus) applied to row crops may cause growth of nuisance algae and other aquatic plants in watershed ponds - a problem called eutrophication. If there are high densities of livestock (pigs or cattle) or poultry, water quality may be seriously degraded, not only from inputs of nutrients, but from ammonia and organic matter. Microbial decomposition of organic matter causes a biochemical oxygen demand (BOD) that can severely reduce oxygen content.

Water Quality for Aquaculture

There is not time to review all water quality variables, so for the time available I shall attempt to summarize a few relevant facts about temperature, dissolved oxygen, pH, carbon dioxide, alkalinity, and ammonia. Books by Boyd (1990a and b) are excellent references on water quality and water quality management for aquaculture.

Temperature

Although sometimes called poikiothermic, meaning that they are cold-blooded, most fish are ectothermal, which means that their body temperature is the same as the surrounding water (tuna and a few other species have body temperatures somewhat higher than the surrounding water, but they are not homothermal, that is they do not have constant body temperature such as mammals or birds). The body temperature of a eurythermal (wide range of temperature adaptation) fish like largemouth bass may range from near freezing to nearly 90°F. It is important to note that intrinsic differences exist in adaptation of fish to water temperature. In regards to their temperature tolerance, fish are categorized as coldwater, coolwater, warmwater, and tropical. Most tropical fish, such as tilapia, die when temperatures are less than 50°F (10°C), and most salmonids (trout and salmon) die when temperatures exceed 80°F (25.7°C). Channel catfish, which are called warmwater fish, survive from near freezing to about 90°F (32.2°C). For each species, there exists upper and lower limits, as well as an optimum range for growth, which changes with development. The temperature for optimum growth of fish is called the SET, standard environmental temperature. The SET for rainbow trout is 59°F (15°C), and 85°F (29.5°C) channel catfish. It must be recognized that designating a fish as coolwater, or warmwater are broad categories, and that variation exists in the optimal temperature for different species that are lumped in the same category. For example, brook, rainbow, and brown trout are coldwater salmonid fishes, but their temperature tolerance differs, brown trout are much more tolerant of high summer temperatures than brown trout. Arctic char, another coldwater fish, have optimum growth at 50-53.6°F (10-12°C), compared with 59°F (15°C) temperatures than rainbow trout.

Because it is impractical to heat or cool large volumes of water in open ponds or single pass flow-through culture systems (i.e., raceways), species selection is usually based on anticipated water temperature. However, it is important to remember that the optimum temperature required for egg incubation, growth and development of larval fish, and for production of a food-size fish can be quite different. The obvious advantage of recycle systems is that of energy conservation, heating water is expensive, but only a small part of total system volume (2-6%) of new water is added each day.

For ectothermal animals—which include bacteria, insects, zooplankton, frogs and turtles as well as fish—temperature is a critical environmental factor that strongly influences feeding and growth. Also, fish are stressed and disease outbreaks occur after a sudden temperature change or when temperatures are chronically near their maximum tolerance. The metabolic rate of ectothermal animals is said to double with each 18°F (10°C) rise in temperature, a relationship called the Q_{10} factor. For example, the recommended (Piper et al. 1982) feeding rate (lb. of pelleted feed per l00 pounds of fish) for 5-6 inch rainbow trout is 1.7 lb. at 50°F (10°C) but 2.3 lb. at 59°F (15°F), a 35% increase over 9°F (5°C), not quite reaching at 1/2 the Q_{10} factor.

Temperature shock, which will stress or cause high mortality of fish, occurs when fish are moved from one environment to another without gradual acclimation ("tempered") to the other temperature. Boyd (1990) reported that 0.2°C/minute (12°C/hour) can be tolerated "provided the total change in temperature does not exceed a few degrees."

It is important to remember that temperature controls the solubility of gases in water, and the reaction rate of chemicals, the toxicity of ammonia, and of chemotherapeutics to fish. In freshwater, at sea level, the solubility of oxygen is 11.3 mg/L at 50°F (10°C), but only 9.0 at 70°F (21.1°C) (Figure 1). Solubility of oxygen also decreases with elevation.

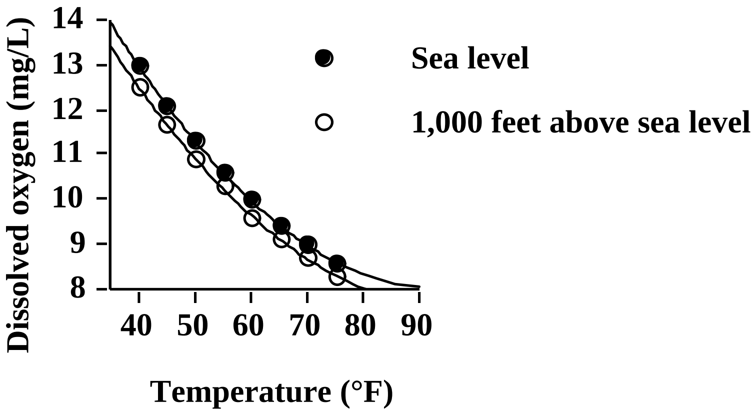

Figure 1. Solubility of oxygen in relation to temperature and elevation

Dissolved Oxygen (DO)

Oxygen is the first limiting factor for growth and well-being of fish. Fish require oxygen for respiration, which physiologists express as mg of oxygen consumed per kilogram of fish per hour (mg O_2/kg/h). The respiratory rate increases with increasing temperature, activity, and following feeding, but decreases with increasing mean weight. here are several important implications of these physiological facts for aquaculture:

- At a given temperature, smaller fish consume more oxygen per unit of body weight than larger fish; or said in another way, for the same total weight of fish in a tank, smaller fish require more oxygen than larger fish
- Actively swimming fish consume more oxygen than resting fish. In raceways, high exchange rates will increase energy expenditures for swimming, and oxygen consumption.
- Oxygen consumption of fish will increase after feeding, multiple feedings per day (3 or more) will result in less variation in oxygen demand than 1 to 2 feedings per day.

If a tank is stocked with fish, over several weeks of a growth cycle, the fish will grow, reducing their consumption rate (inverse OC-fish size relationship), but the density (pounds/cubic ft^3) will increase. Flow to the tank will have to be increased or the population divided to handle the larger oxygen demand. The oxygen consumption rate of fish of different species ranges range from 200-500 (mg O_2/kg/h).

Oxygen concentration in water is expressed as parts per million (ppm), which is equivalent to mg/L, or as a percent of saturation value for that temperature and pressure (altitude). Recall, that oxygen concentration at saturation varies in relationship to water temperature and elevation. Elevation is not of much concern throughout the Midwest because elevation changes are minor, however, in the West, particularly in the Rocky Mountains, elevation changes can be substantial, which can reduce the saturation of oxygen in air saturated water. Oxygen concentration should not be less than 70% of saturation. Blood oxygen capacity decreases with lower pH or high $C0_2$, and increases in temperature not only reduce the saturation level of water, but also reduces oxygen affinity and oxygen capacity of the blood; fish maintain supply to tissues by increased ventilation, as can be seen by opercular movement.

In ponds, the major source of oxygen is from algal photosynthesis and from wind mixing the air and water. In tanks or raceways, oxygen is supplied by the inflowing water, which should be near saturation for the temperature and elevation. In many trout hatcheries, the water is reused, that is it typically passes through a series of raceways (usually not more than 4), with reaeration (oxygenated) by atmospheric contact as the water passes from raceway-to-raceway, or, reaeration may be obtained with mechanically powered aerators or air diffusers supplied by air blowers. Supersaturated oxygen concentrations can be achieved in raceways by addition of "pure" oxygen that is generated on site or purchased as LOX (liquid oxygen) and stored in Dewars (double-walled vacuum storage vessels like thermos bottles). The choice oxygen supply depends on local availability and the amount of oxygen used. Dewars gradually warm and as they warm gas pressure builds up, which must be vented (fizzed off) or the bottle would explode. If consumption rate of a culture facility is rapid, then the Dewar may be the system of choice, it can be a dependable supply of oxygen in an power outage, with normally closed valves that open when the power goes off, oxygen can be supplied automatically.

A common generalization about oxygen requirements for aquaculture is that the minimum DO should be greater than 5 mg/L for growth of warmwater fish and 6 mg/L coldwater fishes at their optimum temperature. Thus, for a raceway or circular tank, oxygen of the effluent water should be at least 5 mg/L. The oxygen available for fish (AO) is the difference between the inflow (O_2) and outflow (O_2) oxygen concentration. If the outflow must be no less than 5 mg/L, then the inflow must be higher than that for fish to have any oxygen for respiration. At a temperature of 60°F (15.5°C), oxygen saturation would be about 9.6 mg/L at 1000 feet, which would provide about 4.6 mg/L of AO for fish respiration (9.6-5.0 = 4.6 mg/L). The oxygen requirement for 100 kg (220 lb.) of fish that consume 300 mg O_2/kg/h would be 30,000 mg O_2/h (100 kg fish x 300 mg/kg/h). Assuming AO of 4.5 mg/L, an inflow of 6,522 L of water (108.7 Lpm, or 28.6 gpm) to supply 100 kg (220 pounds) of fish 30,000 mg/h of oxygen would be needed (30,000 _ 4.6 mg/L) to supply the oxygen consumed. This calculation is not a guide for water flow needed for trout production, Scheffer and Marriage (1969) stated that 450 gpm of high-quality water was needed per 10,000 pounds of annual production (22.2 gpm per pound of production).

At temperatures optimum for growth, fish are stressed at oxygen concentrations less than 5 mg/L. If the condition is chronic, fish stop feeding, growth slows down, stress-related disease begins. For rainbow trout, mortality may begin at 3 mg/L, but channel catfish tolerate less than 2 mg/L before mortality commences. However, if the gills of fish are damaged by parasites (hamburger gill disease is a good example of a severe protozoan disease of the gills of channel catfish), the fish may die when oxygen concentrations drop only slightly below 5 mg/L.

pH, Carbon Dioxide (CO_2) and Alkalinity

The pH of water is an index of hydrogen ion (H^+) activity of water. The pH scale (range from 0 to 14) is logarithmic (base 10), an important fact to remember because a drop of 1 pH unit indicates a 10 fold increase in hydrogen ions (H+) present in water. A pH value may fall anywhere on a scale from 0 (strongly acidic) to 14 (strongly basic or alkaline), with a value of 7 representing neutrality (= 10^{-7} moles/liter of H^+ ions).

The pH of most productive natural waters that are unaffected by pollution is normally in the range of 6.5 to 8.5 at sunrise, typically closer to 7 than 8. Diurnal variation is related to photosynthesis:

$$CO_2 + H_2O \overset{\text{Chlorophyll}}{\underset{\text{Sunlight}}{\Leftrightarrow}} C_6H_{12}O_6 + O_2 \tag{1}$$

The controlling factor for pH in most aquacultural facilities is the relationship between algal photosynthesis, carbon dioxide (CO_2), and the bicarbonate ($HC0_3^-$) buffering system:

$$CO_2 + H_2O \Leftrightarrow H_2C0_3 \Leftrightarrow HC0_3^- + H^+ \tag{2}$$

At night, respiration by bacteria, plants, and animals results in oxygen consumption and carbon dioxide production, the reaction in formula (2) goes from left to right, first producing carbonic acid (H_2C0_3), then bicarbonate $HC0_3^-$ and H^+ ions; the increase in H^+ causes the pH to drop. During sunlight, respiration continues, but algae use CO_2 for photosynthesis, formula (1); the reaction of formula (1) goes from right to left, reducing the abundance of H^+ ions, and pH goes up. In productive ponds, especially those with low alkalinity, the daytime pH may reach 10, which can be lethal to young fish, especially hybrid striped bass.

Fish can die also die from pH shock, a consequence of a sudden change in pH (³ 1.7 pH units) that may occur when moving fish from pond to tank, or tank to pond. Toxicity of other compounds to fish, especially ammonia and chlorine, are affected by pH.

Ammonia

The major source of ammonia in a water of a heavily stocked culture pond or in the effluent of a raceway is from excretion of fish, mostly via their gills. Ammonia is produced by animals as a byproduct of protein metabolism. What is measured by chemical analysis (Nessler method) for ammonia is called total ammonia nitrogen (TAN) because it includes two forms of ammonia: ammonia (NH_3), the unionized form, and the ammonium ion (NH_4^+). The unionized ammonia (UIA) is toxic to fish.

(3) $NH_3 + H_2O \quad \Leftrightarrow \quad NH_4^+ + OH^-$

Low temperature ⇒ ⇐ High temperature
and low pH and high pH

The temperature and pH of water affects the ratio of (NH_4^+):(NH_3) in water. At lower temperatures and lower pH, the reaction (3) shifts from left to right, decreasing the percent of unionized (toxic) form (NH_3) of ammonia (Table 2).

Table 2. Percent unionized (NH_3) ammonia as a function of pH and temperature (from Thurston et al. 1979).

Temperature	**pH**				
°F (°C)	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**
50 (10)	0.0186	0.186	1.83	15.7	65.1
59 (15)	0.0274	0.273	2.66	21.5	73.2
68 (20)	0.0397	0.396	3.82	28.4	79.9
77 (25)	0.0568	0.566	5.38	36.3	85.0
86 (30)	0.0805	0.799	7.45	44.6	89.0

Toxicity from high TAN is more likely at high pH and high temperatures, conditions that occur in mid-summer in ponds with high standing crop of fish, which are also likely to have a heavy algal bloom, and mid-afternoon pH values close to 9. For example, if we assume a TAN value 4.0, a temperature of 86°F (30°C), and a pH of 9, the concentration of the toxic form of TAN would be 1.7 mg/L, 4 x 0.446 (using the ratio not the percent). Would 1.7 mg/L UIA be a problem? For salmonid fishes, it is recommended that the concentration of UIA not exceed 0.0125 to 0.02 mg/L to maintain health of the fish, however, the toxic concentrations of UIA (NH_3) for trout are about 0.32 mg/L for rainbow trout, but 1.50-3.10 for channel catfish (Ruffier et al. 1981, cited by Boyd 1990a). Thus, a UIA of 1.7 mg/L, would be a expected to cause mortality of most fish, and it would be stressful for channel catfish.

Summary

Water quality varies considerably between surface water and groundwater sources, and between sources at different geographical locations. Groundwater is consider the most desirable source of supply, because it has more consistent diurnal and seasonally in qualities than surface water, and much less likely to be contaminated by pathogens or fish. Fish can use some water supplies considered impaired for human use, even some saline waters have aquaculture potential. Water quality affects affect growth and well-being of fish, therefore, water quality should be of great importance to the aquaculturist. A high quality oxygen meter, and a water chemistry kit are essential equipment items for fish farmers who must become accustomed to measuring water quality on a regular basis. It is equally important to know how to interpret the water quality parameters that are measured to maintain the health and well-being of their fish stock.

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