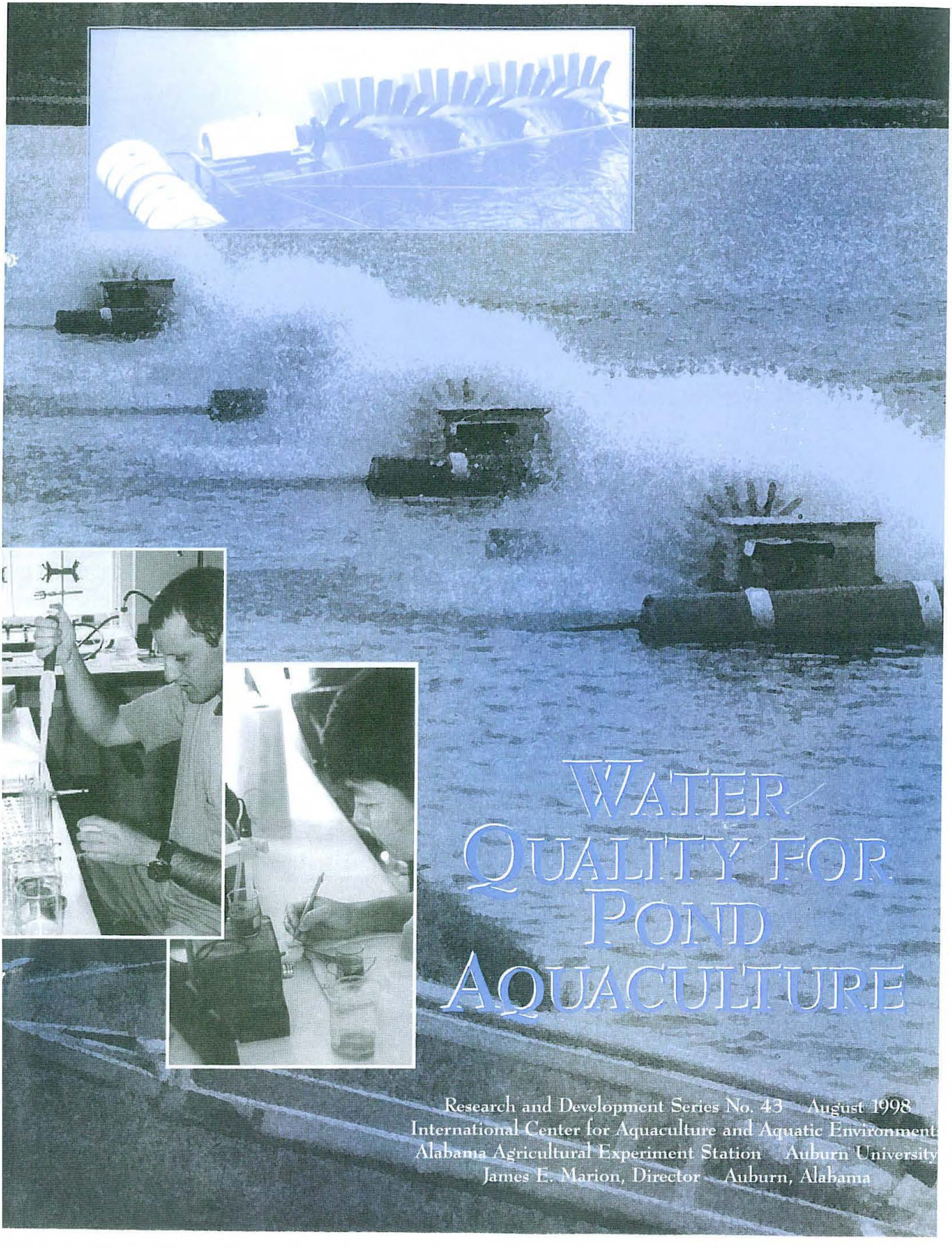

WATER QUALITY FOR POND AQUACULTURE

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James E. Marion, Director Auburn, Alabama

TABLE OF CONTENTS

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WATER QUALITY FOR POND AQUACULTURE

Claude E. Boyd
Department of Fisheries and Allied Aquacultures
Auburn University, Alabama 36849 USA

WATER QUALITY includes all physical, chemical, and biological factors that influence the beneficial use of water. Where aquaculture is concerned, any characteristic of water that affects the survival, reproduction, growth, or management of fish or other aquatic creatures in any way is a water quality variable. There are many water quality variables in pond aquaculture, but only a few of these normally play an important role. These are the variables that aquaculturists should attempt to control by management techniques. All other things being equal, a pond with "good" water quality will produce more and healthier aquatic creatures than a pond with "poor" water quality. A knowledge of water quality principles will help the aquaculturist in determining the potential of a body of water for aquaculture, improving environmental conditions in ponds, avoiding stress-related disease and parasite problems, and ultimately producing aquatic creatures more efficiently.

Scientific papers and books on water quality dynamics and management in ponds are quite technical and detailed. Therefore, Boyd and Lichtkopper *(6)* prepared a simple and concise manual of the major aspects of pond water quality and its management for practical aquaculturists. That publication was popular, but it is now out of print. This manual is a revision of the manual by Boyd and Lichtkoppler. It covers the major water quality variables, including salinity, pH and alkalinity, dissolved oxygen, plankton, nutrients, and toxic metabolites. It explains how these variables relate to the use of fertilizers and feeds to increase production in ponds. It also discusses the improvement of water quality through mechanical aeration and other methods. This manual explains only the usual relationships between water quality variables and aquacultural production and provides some common management methods. All aspects of pond water quality and its management cannot be covered in a small manual or in a simplistic way. Those wanting a more complete account of water quality may consult Boyd *(2)* or Boyd and Tucker *(7)*.

WATER QUALITY PROCESSES AND VARIABLES

TEMPERATURE

Warmwater species grow best at temperatures between 25° and 32°C (Celsius). Water temperatures are in this range year-round at low altitudes in the tropics, but water temperatures are too low in winter in temperate regions for rapid growth of warmwater aquaculture species and their food organisms. For this reason, management procedures such as feeding and fertilizing are halted or reduced in winter in temperate climates.

Temperature has a pronounced effect on chemical and biological processes. In general, rates of chemical and biological reactions double for every 10°C increase in temperature. This means that aquatic organisms will use twice as much dissolved oxygen at 30°C as at 20°C, and chemical reactions will progress twice as fast at 30°C as at 20°C. Therefore, dissolved oxygen requirements of aquatic creatures are more critical in warm water than in cooler water. Chemical treatments of ponds also are affected by temperature. In warm water, fertilizers dissolve faster, herbicides act quicker, rotenone degrades faster, and the rate of oxygen consumption by decaying organic matter is greater.

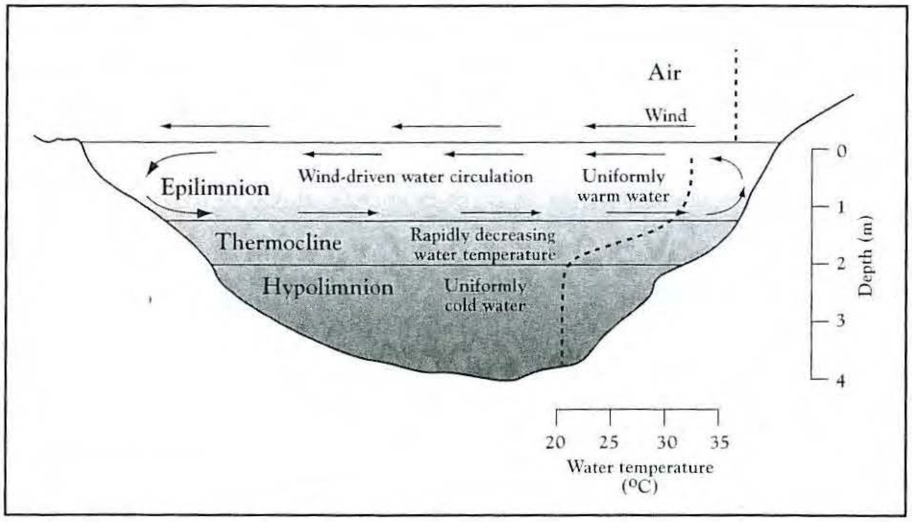

Figure 1. Thermal stratification in a relatively deep pond.

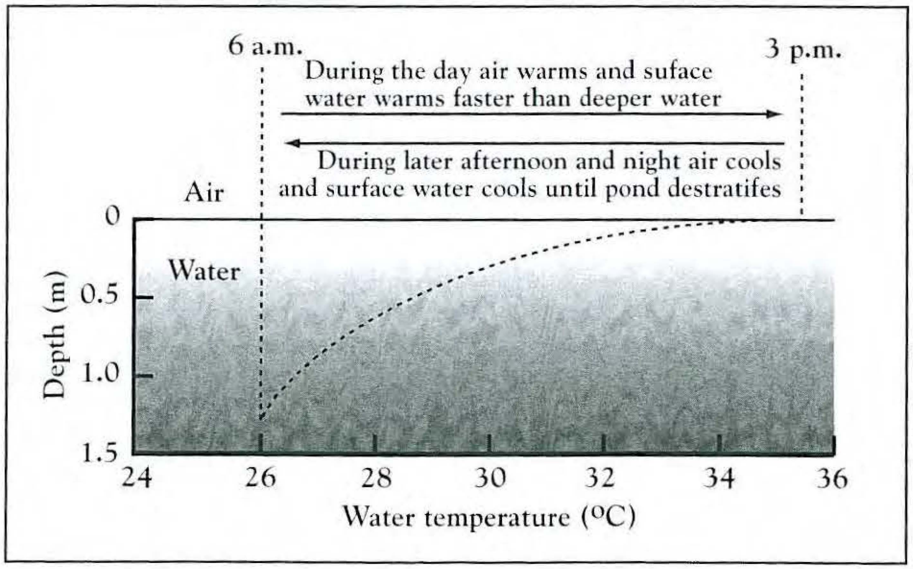

Figure 2. Daily thermal stratification and destratification in a shallow aquaculture pond.

In ponds, heat enters at the surface and surface waters heat faster than deeper waters. Because the density of water (weight per unit volume) decreases with increasing temperature above 4°C, surface waters may become so warm and light that they do not mix with the cooler, heavier waters of deeper layers. The separation of pond waters into distinct warm and cool layers is called thermal stratification. The upper, warm layer is called the epilimnion and the lower, cooler layer is known as the hypolimnion. The layer of rapidly changing temperature between the epilimnion and the hypolimnion is termed the thermocline.

The temperature profile for a thermally stratified pond is shown in figure 1. In temperate regions, large ponds may stratify in the spring and remain stratified until fall. In small, shallow ponds in temperate regions and in tropical ponds, stratification often exhibits a daily pattern. During the day, the surface waters warm and form a distinct layer. At night the surface waters cool to the same temperature as the lower waters and the two layers mix (figure 2). An extensive discussion on thermal stratification may be found in any standard text on limnology.

In some climates, pond surface waters may reach temperatures of 35°C or more. This is above the optimum temperature for most warmwater species, but the creatures may seek haven from the high temperature in deeper waters. Fish and crustaceans have poor tolerance to sudden changes in temperature. One should not remove them from water of one temperature and suddenly thrust them into a water of appreciably higher or lower temperature.

Often a sudden change in temperature of as little as 3° or 4°C will stress or even kill aquatic creatures. The effect is usually worse when moving creatures from cooler to warmer water. Because temperatures increase with decreasing altitude, one must allow for temperature adjustment when moving aquatic creatures from high altitude to low altitude waters. Aquaculture species readily tolerate gradual changes in temperature. For example, one could raise the water temperature several degrees over a few hours without harming aquatic creatures, but if they are suddenly removed from cool water and placed in water that is several degrees warmer they might die.

PHOTOSYNTHESIS AND RESPIRATION

In ponds, plants are the primary source of organic matter that ultimately finds its way into aquatic animal flesh. Plants have the ability to use carbon dioxide (CO_2), water (H_2O), mineral nutrients, and sunlight to produce organic matter in the form of simple sugar ($C_6H_{12}O_6$), and oxygen (O_2) is formed as a by-product. In this process, termed photosynthesis, inorganic carbon in carbon dioxide is chemically reduced to organic carbon in sugar. Light energy (sunlight) is transformed to chemical energy of sugar. The summary reaction for photosynthesis is:

$$\text{Light Energy} + 6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2.$$

The simple sugar molecules produced by green plants through photosynthesis represent nearly all of the energy available to living things. Both plants and creatures depend upon photosynthetically produced energy. The simple sugar molecules also are the building blocks for more complex organic compounds. Plants make complex carbohydrates (starch, cellulose, etc.), proteins, fats, vitamins, and other compounds from the sugars formed in photosynthesis. Plants also make their tissues from these compounds and use photosynthetically derived sugar as an energy source. Creatures cannot produce organic matter. They must feed directly on plants or on other creatures that have fed on plants. All energy, nutrients, and structural materials needed by creatures come originally from plants.

Respiration is a second basic process in aquaculture. In respiration, organic matter is combined with oxygen (oxidized) with the release of water, carbon dioxide, and energy. Plant and animal cells have the ability to capture some of the energy released through oxidation and to use it to do biological work. The rest is lost as heat. From an ecological standpoint, respiration is the reverse of photosynthesis:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O) + \text{heat energy}.$$

In photosynthesis, carbon dioxide is reduced to organic carbon with the capture of energy and the release of oxygen, while in respiration, organic carbon is oxidized to carbon dioxide with the release of energy and the uptake of oxygen. Biochemically, photosynthesis and respiration are quite distinct processes, but for ecological purposes, photosynthesis and respiration may be thought of as reversible reactions. When photosynthesis is progressing faster than respiration, oxygen will accumulate and carbon dioxide will decline. This is the usual situation in a pond during daylight. At night, photosynthesis stops but respiration must continue day and night. Thus, at night oxygen declines and carbon dioxide increases.

TABLE 1. TYPICAL CONCENTRATIONS OF ELEMENTS IN POND WATER AND PHYTOPLANKTON [1]

Element	Water (ppm)	Phytoplankton (ppm wet weight)	Concentration factor
Carbon	10	9,500	950
Nitrogen	0.1	1,600	16,000
Phosphorus	0.005	165	33,000
Sulfur	2.5	125	50
Chloride	5.0	25	5
Calcium	10.0	100	10
Magnesium	2.0	50	25
Potassium	1.0	150	150
Sodium	3.0	1,050	350
Iron	0.1	30	300
Manganese	0.05	15	300
Zinc	0.005	1.25	250
Copper	0.005	3.0	600
Boron	0.02	0.7	35

[1] Concentration factors were obtained by dividing concentrations in phytoplankton by concentrations in water.

The food chain or food web in an aquaculture pond (figure 3) initiates with plants. In ponds the most desirable plants are phytoplankton. These organisms are microscopic algae that are suspended in the water. Algae often are green in color, but some may be blue-green, yellow, red, black, or brown. When pond water contains enough algae to be discolored, it is said to contain a "phytoplankton bloom" or, more generally, a "plankton bloom." Algae can grow on the pond bottom where there is sufficient light for photosynthesis. The phytoplankton (algae) may be fed upon by microscopic creatures called zooplankton. Collectively phytoplankton and zooplankton are called plankton. The plankton die and fragment to form dead organic matter (detritus) which is food

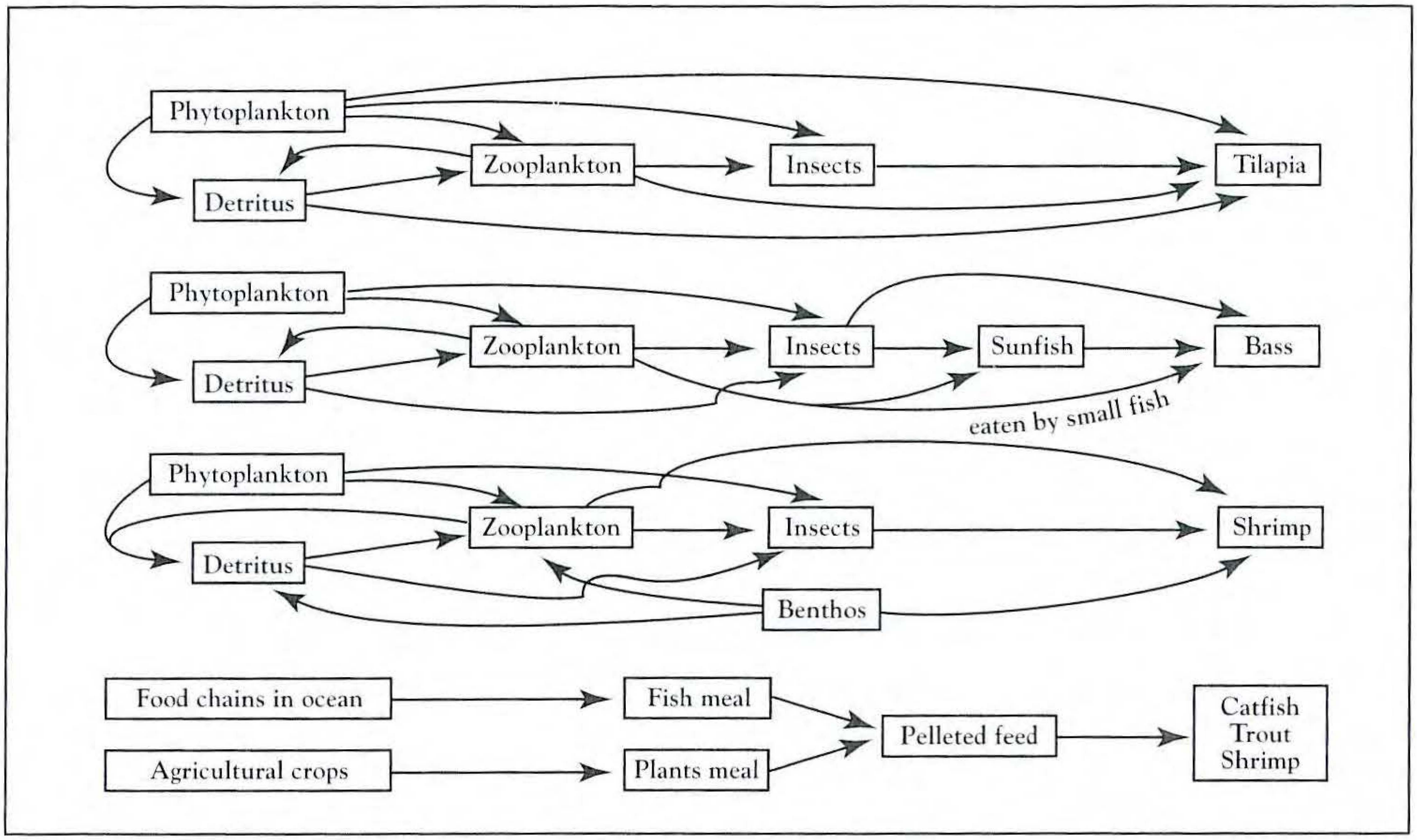

Figure 3. The food webs in aquaculture ponds.

for bacteria, fungi, and various creatures. Detritus settles to the pond bottom; this enriches the soil with organic matter. The pond bottom supports a community of bacteria, fungi, algae, and small creatures that is called the benthos. Aquatic insects are abundant in ponds and feed on plankton, benthos, or detritus. In the shallow areas of ponds with clear water, larger aquatic plants (macrophytes) may grow. Aquatic macrophytes also may grow while floating on the pond surface. Few fish or other creatures feed directly on macrophytes and their large structure obstructs the water; therefore, macrophytes are normally undesirable in aquaculture ponds. Depending upon the species, aquaculture creatures eat plankton, benthos, detritus, aquatic insects, small fish and crustaceans, or some combination of these food organisms. Some species of fish even eat macrophytes, and species such as the grass carp can be used for controlling macrophytes in ponds.

In order to increase production in ponds, it is necessary to increase the amount of food. This can be done by improving conditions for production of phytoplankton, which, in turn, will increase the production of other natural food organisms. Usually, it is only necessary to add to ponds certain inorganic nutrients in the form of manure or chemical fertilizer to increase phytoplankton growth. Of course, in aquaculture, manufactured feed is commonly added to ponds which short-circuits the food chain. Additions of manufactured feed allow more production than can be achieved in fertilized ponds, but feeding does not change the dependence of aquaculture on plants. Aquaculture feeds are made from plant products or from animal products which were derived from a plant-based food web.

Phytoplankton is extremely important in the dynamics of dissolved oxygen concentrations in ponds. As phytoplankton growth is enhanced by nutrients from fertilizers and feeds, wide swings in dissolved oxygen concentration in water occur between night and day. Excessive phytoplankton blooms may lead to an oxygen depletion and associated stress or mortality of aquatic creatures at night and oxygen supersaturation of surface water during daytime. Water quality in ponds is to a large degree dominated by phytoplankton abundance and the balance between photosynthesis and respiration.

SUBSTANCES IN WATER

Inorganic Substances

Dissolved inorganic substances in water include almost every element in the earth's crust and atmosphere. Seven ions (sodium, potassium, calcium, magnesium, chloride, sulfate, and bicarbonate) normally contribute 95% or more of the weight of the dissolved ions in water. Other ions (for example, phosphate, ammonium, and nitrate) are extremely important biologically in spite of their relatively low concentrations.

A large number of inorganic elements are required for plant growth. Most species require at least the following: carbon, hydrogen, oxygen, nitrogen, sulfur, phosphorus, chloride, boron, molybdenum, calcium, magnesium, sodium, potassium, zinc, copper, iron, and manganese. Diatoms (species of algae) also require silicon. Aquatic plants make oxygen in photosynthesis, and they obtain hydrogen from water. Carbon dioxide enters water from the air and from respiration by bacterial decomposition of organic matter and other living plants and creatures in the water. The other elements enter ponds from the water supply, from dissolution of minerals in the pond bottom, or in additions of fertilizer and feed. Of course, some algae and bacteria are able to fix nitrogen. That is, they can take molecular nitrogen (N_2), which enters water from the air, and convert this nitrogen to organic nitrogen in plant tissue.

Nitrogen and phosphorus are more likely to limit phytoplankton growth than other nutrients. Typical concentrations of plant nutrients in pond water and in phytoplankton biomass are shown in table 1. Concentration factors indicate how much each element is accumulated by phytoplankton above its concentration in pond water. Less nitrogen and phosphorus is found in pond water relative to phytoplankton needs than for other elements. Hence, fertilizers are added to ponds to supplement the natural shortage of nitrogen and phosphorus. Brackishwater ponds contain greater concentrations of sulfate, chloride, calcium, magnesium, potassium, and boron than reported in table 1 for freshwater ponds. However, concentrations of other nutrients are similar between freshwater and brackishwater ponds, and nitrogen and phosphorus also are key nutrients in fertilization of brackishwater ponds.

TABLE 2. ACCEPTABLE CONCENTRATION RANGES FOR DISSOLVED INORGANIC SUBSTANCES IN AQUACULTURE POND WATERS

Element	Form in water	Desired concentration
Oxygen	Molecular oxygen (O_2)	5 - 15 mg/liter
Hydrogen	H^+ [$-\log(H^+) = pH$]	pH 7 - 9
Nitrogen	Molecular nitrogen (N_2)	Saturation or less
	Ammonium (NH_4^+)	0.2 - 2 mg/liter
	Ammonia (NH_3)	< 0.1 mg/liter
	Nitrate (NO_3^-)	0.2 - 10 mg/liter
	Nitrite (NO_2^-)	< 0.3 mg/liter
Sulfur	Sulfate (SO_4^{2-})	5 - 100 mg/liter (freshwater) < 3,000 mg/liter (brackishwater)
	Hydrogen sulfide (H_2S)	Not detectable
Carbon	Carbon dioxide (CO_2)	1 - 10 mg/liter
Calcium	Calcium ion (Ca^{2+})	5 - 100 mg/liter (freshwater) < 500 mg/liter (brackishwater)
Magnesium	Magnesium ion (Mg^{2+})	5 - 100 mg/liter (freshwater) < 1,500 mg/liter (brackishwater)
Sodium	Sodium (Na^+)	2 - 100 mg/liter (freshwater) < 11,000 mg/liter (brackishwater)
Potassium	Potassium ion (K^+)	1 - 10 mg/liter (freshwater) < 400 mg/liter (brackishwater)
Bicarbonate	Bicarbonate ion (HCO_3^-)	20 - 300 mg/liter (sportfish and most ponds with feeding) 50 - 300 mg/liter (tilapia and crustacean ponds)
Carbonate	Carbonate ion (CO_3^{2-})	0 - 20 mg/liter
Chloride	Chloride ion (Cl^-)	1 - 100 mg/liter (freshwater) < 20,000 mg/liter (brackishwater)
Phosphorus	Phosphate ion (HPO_4^{2-}), $H_2PO_4^-$)	0.005 - 0.2 mg/liter
Silicon	Silicate (H_2SiO_3, $HSiO_3^-$)	2 - 20 mg/liter
Iron[1]	Ferrous iron (Fe^{2+})	0 mg/liter
	Ferric iron (Fe^{3+})	Trace
	Total iron	0.05 - 0.5 mg/liter
Manganese[1]	Manganese ion (Mn^{2+})	0 mg/liter
	Manganese dioxide (MnO_2)	Trace
	Total manganese	0.05 - 0.2 mg/liter
Zinc[1]	Zinc ion (Zn^{2+})	< 0.01 mg/liter
	Total zinc	0.01 - 0.05 mg/liter
Copper[1]	Copper ion (Cu^{2+})	< 0.005 mg/liter
	Total copper	0.005 - 0.01 mg/liter
Boron[1]	Borate (H_3BO_3, $H_2BO_3^-$)	0.05 - 1 mg/liter
Molybdenum[1]	Molybdate (MoO_3)	Trace
Salinity	Sum of all ions	50 - 2,000 mg/liter (freshwater) 2,000 - 35,000 mg/liter (brackishwater)

[1] The desirable ranges for these substances are poorly understood. The values listed as the desired concentrations are actually the usual concentrations of these six trace metals in surface waters of ponds.

After nitrogen and phosphorus, carbon is the next most common element to limit productivity in aquaculture ponds. The availability of carbon is particularly low in acidic waters and in waters of high pH. Applications of agricultural limestone are used to neutralize acidity and enhance alkalinity and carbon availability in acidic ponds. The only economical way of improving carbon availability in high pH water is to add organic matter that decomposes to release carbon dioxide. Low concentrations of trace metals are seldom limiting to phytoplankton growth in ponds, but excessive concentrations in polluted water supplies can be toxic.

Aquatic creatures need adequate concentrations of ions to satisfy their osmotic needs as will be discussed later, but they do not have strict requirements for individual ions. High concentrations of heavy metals can be toxic to aquatic creatures. The concentration of dissolved oxygen in the water is a critical factor in the reproduction, growth, survival, and disease tolerance of aquaculture creatures. The forms of the various inorganic substances and their desired ranges are provided in table 2.

In addition to the dissolved inorganic substances, pond water may contain suspended inorganic soil particles. These particles usually enter ponds in the water supply (runoff is often turbid), or they are suspended in water by wave action or water currents caused by mechanical aeration or wind. The larger particles will settle to the pond bottom, but some of the smaller particles may remain suspended for long periods and cause turbidity. Turbidity by soil particles is undesirable when it restricts light penetration into the water to less than 20 to 25 centimeters.

Organic Substances

A wide range of organic substances occurs in pond water. Dissolved compounds include sugars, starches, amino acids, polypeptides, proteins, fatty acids, tannins, humic acids, vitamins, etc. Large particles of decaying organic matter called detritus also are plentiful. Of course, the plankton and bacteria also contribute to the organic load in water. It is not convenient to analyze for specific organic compounds. Usually, the total weight of organic matter or the total weight of particulate organic matter in water is determined. Desirable ranges for organic matter concentrations are not known, but pond water usually contains less than 50 milligrams per liter of organic matter.

Organic substances in water, particularly plankton, cause turbidity. Turbidity caused by plankton is desirable while turbidity caused by suspended clay particles is not. Ponds are most productive when turbidity by plankton restricts visibility in water to 20 to 40 centimeters. At this level of plankton abundance, natural food is adequate, dissolved oxygen for aquatic creatures is usually available, and light does not penetrate to the pond bottom to encourage growth of rooted aquatic macrophytes. Floating aquatic macrophytes such as water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiodes*), duckweed (*Lemna* sp.), etc., cannot be controlled by turbidity.

SALINITY AND TOTAL DISSOLVED SOLIDS

The total concentration of all dissolved ions is salinity. In freshwater, salinity usually is expressed in milligrams per liter. In humid areas, inland waters usually contain 50 to 250 milligrams per liter salinity. For reference, water with more than 500 milligrams per liter salinity usually is not suitable for domestic purposes, and 1,000 milligrams per liter salinity will impart a salty taste. In arid regions, and even during the dry season in certain humid areas, inland waters can become quite saline. For example, inland ponds in arid regions such as Western Australia or the western United States often have a salinity of 3,000 to 5,000 milligrams per liter. Most freshwater fish can do well in waters with a salinity up to 2,000 milligrams per liter; some species tolerate a much higher salinity.

In brackishwater ponds, the salinity varies with the salinity of the source water. Ocean water usually has about 35,000 milligrams per liter salinity, but water of estuaries may be similar to freshwater in the rainy season and have much higher salinity in the dry season. Some estuaries with limited connections to the sea have a salinity greater than ocean water in the dry season because ions are concentrated through evaporation. Salinity decreases with distance upstream from the mouth of estuaries, and salinity may be stratified with depth in estuaries.

Normally, the salinity of brackishwater is reported in parts per thousand instead of milligrams per liter. One part per thousand is 1,000 milligrams per liter. Brackishwater species can tolerate wide fluctuations in salinity. Marine shrimp, such as *Penaeus vannamei and P. monodon*, can be cultured successfully in coastal ponds over the salinity range of one to 40 parts per thousand. However, most shrimp farmers prefer a salinity of 20 to 25 parts per thousand in their ponds. Annual variation in salinity of a shrimp pond in Ecuador is provided in figure 4. Notice that salinity is clearly related to rainfall.

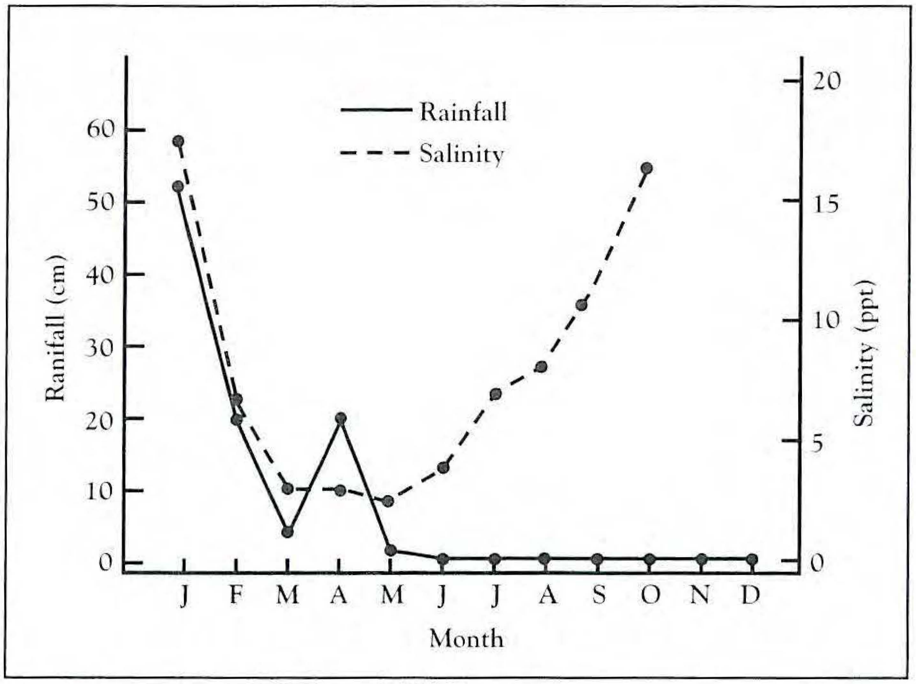

Figure 4. Relationship between rainfall and salinity in shrimp ponds near Guayaquil, Ecuador.

The total concentration of all dissolved substances in water is the total dissolved solids. Usually, concentrations of salinity and total dissolved solids are similar.

TOTAL ALKALINITY AND TOTAL HARDNESS

The total concentration of bases in water expressed in milligrams per liter of equivalent calcium carbonate ($CaCO_3$) is the total alkalinity. Bases in water include hydroxide, ammonia, borate, phosphate, silicate, bicarbonate, and carbonate, but in most pond waters, bicarbonate and carbonate are found in greater concentration than other bases.

The total alkalinity in water is derived mainly from the dissolution of limestone in soils, so the concentration of total alkalinity is determined primarily by soil characteristics. For example, ponds in areas with sandy soils often have a total alkalinity below 20 milligrams per liter, while ponds in areas with calcareous soils may have a total alkalinity above 100 milligrams per liter. Other factors being equal, total alkalinity will be higher in ponds in arid regions than in ponds of humid areas.

The natural fertility of pond water increases with increasing total alkalinity up to at least 150 milligrams per liter *(2)*. However, ponds with a total alkalinity above 20 milligrams per liter can produce an abundance of fish and other aquatic creatures. If the alkalinity is below 20 milligrams per liter, liming is necessary.

The total concentration of all divalent cations in water expressed in terms of milligrams per liter of calcium carbonate is the total hardness. (Divalent cations are positively charged ions with a valence of 2.) Calcium and magnesium are the dominant divalent cations in nearly all pond waters. As a general rule, hardness, like alkalinity, is derived from the dissolution of limestone. When limestone dissolves, it gives equal amounts of hardness and alkalinity. In most waters, total hardness and total alkalinity concentrations are approximately equal. However, some notable exceptions are found. In arid regions, carbonates tend to precipitate out as salinity increases and this causes alkalinity to be lower than hardness. In highly acidic waters, hardness is often higher than alkalinity because bicarbonate is neutralized by the acidity but the hardness ions remain. In some coastal areas, well waters may have alkalinity much higher than the hardness because of the exchange of sodium for calcium in aquifers. Well waters of this type are said to be naturally softened. When such waters are used to fill ponds, photosynthesis may cause high pH. Some examples of total alkalinity, total hardness, and pH in pond water from different climatic and geologic regions are provided in table 3. The desirable range for total hardness is the same as for total alkalinity.

TABLE 3. TOTAL VALUES FOR TOTAL ALKALINITY, TOTAL HARDNESS, AND PH IN WATERS OF PONDS LOCATED AT SITES OF DIFFERENT TYPES

Pond situation	Total alkalinity (mg/liter)	Total hardiness (mg/liter)	pH Morning	pH Afternoon
Humid region, acidic soil	5 - 15	5 - 20	6.5 - 7.5	8.5 - 9.5
Humid region, calcareous soil	75 - 250	75 - 250	7.5 - 8.0	8.0 - 9.0
Arid region	150 - 300	200 - 700	7.5 - 8.5	8.5 - 9.5
Filled by water from well with naturally softened water	100 - 500	5 - 20	8.0 - 8.5	9.0 - 11.0
Brackishwater	75 - 125	1,000 - 6,000	7.5 - 8.0	8.5 - 9.0

ACIDITY

Carbon dioxide is acidic, but normally it cannot depress the pH of water below 4.5. Waters that have a lower pH contain a strong mineral acid—usually sulfuric acid. Such waters are not alkaline, and they are unfit for aquaculture.

The mineral acidity of water is a measure of the total acids in water expressed in terms of milligrams per liter of equivalent calcium carbonate. You can think of mineral acidity as negative alkalinity, because it represents the amount of calcium carbonate that would have to be added to water to raise the pH to the point that addition of more calcium carbonate would cause alkalinity.

BIOCHEMICAL AND CHEMICAL OXYGEN DEMAND

The rate of oxygen consumption by the plankton and bacteria in a sample of pond water is measured to determine the biochemical oxygen demand. A sample of raw water or diluted water is incubated in the dark for five days at 20°C. The loss of dissolved oxygen from the water during the incubation period is the biochemical oxygen demand (BOD). Aquaculture ponds typically have BOD values of five to 20 milligrams per liter. The higher the BOD, the greater the degree of enrichment of pond water with organic matter. Although BOD often has been measured in pond waters, the desirable range is not well defined. Oxygen depletion is a danger in ponds without mechanical aeration when BOD exceeds 20 milligrams per liter.

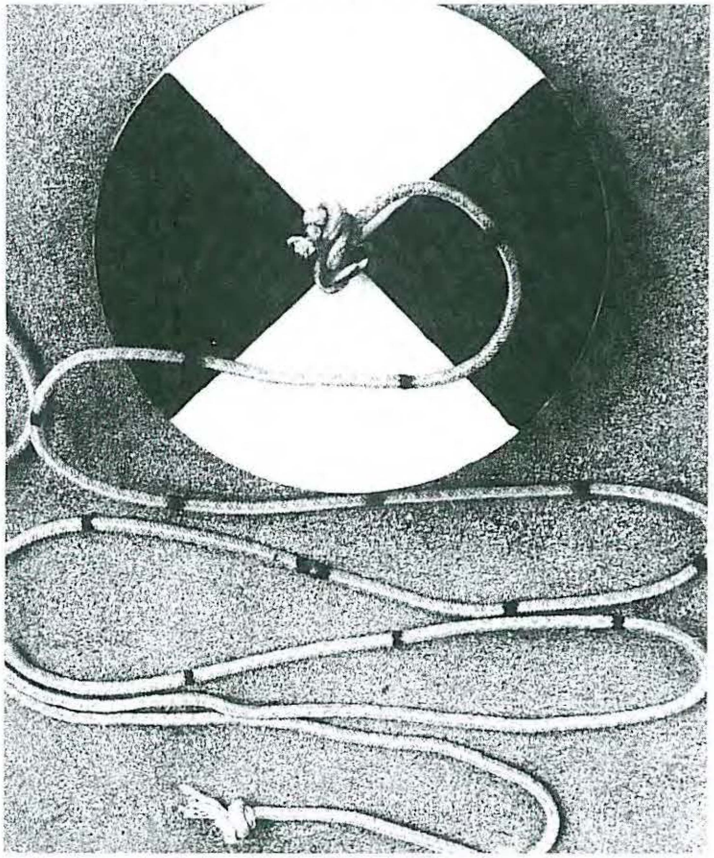

Figure 5. A Secchi disk.

Chemical oxygen demand is measured by converting all of the organic matter in a water sample to carbon dioxide and water by oxidation with potassium dichromate and sulfuric acid. The amount of potassium dichromate consumed in the oxidation is measured and the oxygen equivalent of the dichromate is the chemical oxygen demand (COD). For example, if a sample has a COD of 50 milligrams per liter, 50 milligrams per liter of oxygen would be necessary to oxidize completely the organic matter. The COD is an index of the organic enrichment of pond water. The COD of pond waters may range from less than 10 to more than 200 milligrams per liter. The usual range is 40 to 80 milligrams per liter.

The BOD and COD are not used much in aquaculture pond management, but they are commonly used in estimating the strength of pollutants in effluents. Because of the recent concern over the influence of pond effluents on water bodies into which they are released, environmental management is expected to become a major issue in aquaculture. Thus, the aquaculturist should be familiar with BOD and COD.

SECCHI DISK VISIBILITY

The Secchi disk is a 20-centimeter diameter disk painted with alternate black and white quadrants (figure 5). It is weighted under the bottom and attached at the center of its upper surface with a calibrated line. The depth at which the disk just disappears from view is the Secchi disk visibility. Obviously, care must be taken to standardize the procedure for reading the Secchi disk. In many waters, there is a close correlation between Secchi disk visibility and plankton abundance. As plankton density increases, visibility decreases. However, if waters contain much turbidity from suspended clay particles or detritus, the Secchi disk visibility will not be suggestive of phytoplankton abundance. The general relationship between Secchi disk visibility and the condition of the plankton is provided in table 4.

CHLOROPHYLL A AND PRIMARY PRODUCTIVITY

It is possible to measure the chlorophyll *a* concentration and use it as an index of the abundance of phytoplankton. In general, as the chlorophyll *a* concentration increases, phytoplankton abundance increases. Productive aquaculture ponds often have chlorophyll *a* concentrations of 50 to 200 micrograms per liter (0.05 to 0.2 milligrams per liter).

Primary productivity is an estimate of the amount of organic matter fixed by photosynthesis. In ponds, phytoplankton usually is the largest producer of organic matter. Rates of primary productivity usually are expressed in grams of carbon fixed per square meter per day. Although the aquaculture literature is replete with references to chlorophyll *a* and primary productivity, it is seldom feasible to measure these two variables in practical aquaculture. The Secchi disk visibility is a simpler method for assessing plankton abundance.

TABLE 4. RELATIONSHIP BETWEEN SECCHI DISK VISIBILITIES AND CONDITIONS OF PHYTOPLANKTON BLOOMS

Secchi disk reading (cm)	Comments
Less than 20 cm	Pond too turbid. If pond is turbid with phytoplankton, there will be problems with low dissolved oxygen concentrations. When turbidity is from suspended soil particles, productivity will be low
20-30 cm	Turbidity becoming excessive
30-45 cm	If turbidity is from phytoplankton, pond is in good condition
45-60 cm	Phytoplankton becoming scarce
More than 60 cm	Water is too clear. Inadequate productivity and danger of aquatic weed problems

SUSPENDED SOLIDS, TURBIDITY, AND COLOR

The term turbid indicates that water contains suspended material which interferes with the passage of light. In aquaculture ponds, turbidity which results from planktonic organisms is a desirable trait, whereas turbidity caused by suspended clay particles is undesirable. Even with the later condition, the clay particles are seldom abundant enough in water to directly harm aquatic creatures. If the pond receives runoff that carries heavy loads of silt and clay, the silt settles over the pond bottom and smothers fish eggs and benthic organisms. The finer clay particles which remain in suspension restrict light penetration and limit the growth of plants. A persistent clay turbidity that restricts visibility into the water to 30 centimeters or less may prevent development of plankton blooms. Methods for controlling clay turbidity will be discussed later.

Some ponds receive large inputs of vegetative matter from their watersheds. Extracts from this plant material (humates) often impart color to the water. Color from vegetative extracts often appears as a dark stain, giving the water the appearance of tea or weak coffee. Pond waters with high concentrations of humates are typically quite acidic and have a low total alkalinity. Although color does not adversely affect aquatic creatures directly, it restricts light penetration and reduces plant growth. Agricultural limestone applications have been used to successfully remove humates from natural waters.

In addition to color, the water may have scum, foam, bubbles, and other material on the surface. Scums often result from floating algae or pollen. Foam usually results from protein in the water, and bubbles result from dissolved oxygen supersaturation or release of methane, carbon dioxide, and other gas from decomposition of organic matter.

The suspended solids that impart turbidity to water are measured by weighing the amount of material retained when pond water is passed through a fine filter. Suspended solid concentrations often range from 10 to 50 milligrams per liter, but higher concentrations may occur in very turbid ponds. The turbidity is estimated from the amount of light that is adsorbed by a water sample. Instruments called nephelometers or turbidimeters are used to make turbidity measurements. Turbidity often ranges from 10 to 50 nephelometer turbidity units in ponds. Practical aquaculturists seldom measure suspended solids or turbidity; they rely upon Secchi disk visibility to evaluate turbidity of pond water.

It is not unusual for aquaculturists to observe and record the color of water. Color results from suspended and dissolved substances, and when color is changing, water quality conditions and especially phytoplankton communities also are changing. Some farmers have observed their ponds enough to predict the suitability of their water for fish culture from Secchi disk visibility, color, and appearance.

pH

The pH is defined as the negative logarithm of the hydrogen ion (H+) concentration:

$$pH = -\log [H^+].$$

More simply, pH indicates how acidic or basic a water is. For practical purposes, water with a pH of 7 is considered neither acidic nor basic; it is said to be neutral. Water with a pH below 7, is acidic. Water with a pH above 7 is considered basic. The pH scale extends from 0 to 14; the more the pH differs from 7, the more acidic or basic a water.

TABLE 5. THE EFFECT OF pH ON POND FISH AND CRUSTACEANS

pH	Effect
4	Acid death point
4-5	No reproduction
5-6	Slow growth
6-9	Best growth
9-11	Slow growth
11	Alkaline death point

The pH of most freshwater ponds is between 6 and 9, and within a given pond, there often is a daily fluctuation in pH of one or two units. Brackishwater ponds usually have pH values of 8 to 9, and daily pH fluctuations usually are less than in freshwater ponds. Daily fluctuation in pH results from changes in the rate of photosynthesis by phytoplankton and other aquatic plants in response to the daily photoperiod. Carbon dioxide is acidic as shown in the following equation:

$$CO_2 + H_2O = HCO_3^- + H^+.$$

If carbon dioxide concentration increases, hydrogen ion concentration increases and pH decreases. Conversely, if carbon dioxide concentration decreases, hydrogen ion concentration falls and pH rises. Thus, when phytoplankton remove carbon dioxide from the water during daylight, the pH of water increases. At night, no carbon dioxide is removed from the water by phytoplankton, but all pond organisms release carbon dioxide in respiration. As carbon dioxide accumulates in the water at night, the pH falls. The daily cycle in pH is illustrated in figure 6. The daily fluctuation in pH is not always as great as shown in this figure, but wide pH fluctuation can result when phytoplankton are abundant. Ponds with moderate or high total alkalinity usually have higher pH values in the early morning than ponds with low total alkalinity. However, when phytoplankton are abundant, much higher afternoon pH values occur in ponds with low alkalinity than in ponds with greater alkalinity. This results because of the buffering capacity afforded by the higher alkalinity.

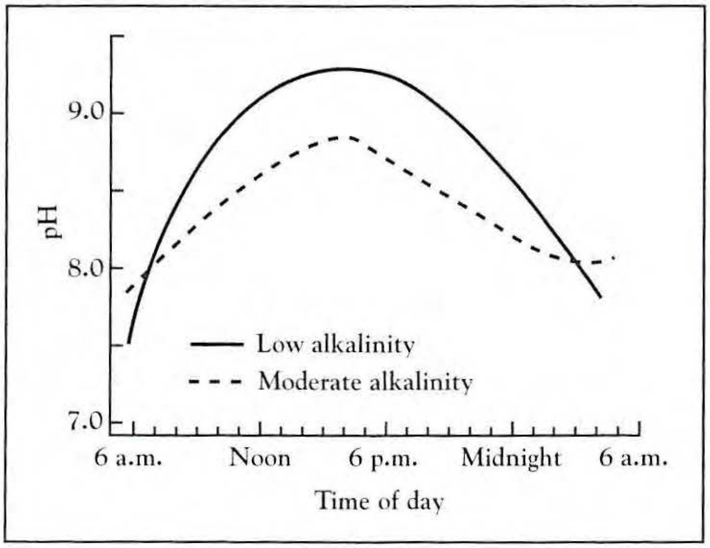

Figure 6. Daily fluctuation in pH in fish culture ponds.

The direct influence of pH on pond fish and crustaceans is presented in table 5. There are, however, exceptions to these effects. For example, some Amazon River fish live and reproduce in waters of pH 4.0 to 4.5. In surface waters, brief occurrences of pH above 9, which are common in aquaculture ponds, normally do not harm aquaculture species.

Where the pH of pond water is too low, lime may be applied to improve pH. Low pH is more common than high pH. This is fortunate, for there is no really reliable procedure for reducing high pH. Usually, acidity problems in ponds do not result from direct effects of low pH on growth, reproduction, or survival, but from the effects of low alkalinity and acidic muds on plankton and benthic production *(3)*. The effects, of course, are reflected in low production of fish and other culture species. In some coastal areas, soils contain from 1 to 5% sulfur in the form of iron pyrite. Such soils are called potential acid sulfate soils. If ponds are built in such material and pyritic soil is exposed to the air in levees or watershed, oxidation of pyrite can result in the formation of sulfuric acid. This acid can leach into ponds and cause an extremely low pH. Iron pyrite often is associated with coal deposits, and drainage from coal mines also may contain sulfuric acid from oxidation of pyrite and have a very low pH.

DISSOLVED OXYGEN

Dissolved oxygen is the most critical water quality variable in aquaculture. Aquaculturists need to thoroughly understand factors affecting the concentration of dissolved oxygen in pond water. They also should be aware of the influence of low dissolved oxygen concentrations on aquaculture species.

Solubility

The atmosphere contains 20.95% oxygen. At standard atmospheric pressure (760 millimeters of mercury), the pressure of oxygen in air is 159.2 millimeters (760 X 0.2095). The pressure of oxygen in air drives oxygen into water until the pressure of oxygen in water is equal to the pressure of oxygen in air. When the pressure of oxygen in water and air is equal, net movement of oxygen from air to water ceases, and dissolved oxygen is said to be at equilibrium or saturation.

The solubilities of dissolved oxygen at saturation for standard atmospheric pressure and different tempera-

TABLE 6. THE SOLUBILITY OF OXYGEN (MG/LITER) IN WATER AT DIFFERENT TEMPERATURES AND SALINITIES FROM MOIST AIR WITH PRESSURE OF 760 MM HG. AFTER COLT (9)

Temperature (°C)	Salinity (ppt)								
	0	5	10	15	20	25	30	35	40
0	14.60	14.11	13.64	13.18	12.74	12.31	11.90	11.50	11.11
1	14.20	13.72	13.27	12.82	12.40	11.98	11.58	11.20	10.82
2	13.81	13.36	12.91	12.49	12.07	11.67	11.29	10.91	10.55
3	13.44	13.00	12.58	12.16	11.76	11.38	11.00	10.64	10.29
4	13.09	12.67	12.25	11.85	11.47	11.09	10.73	10.38	10.04
5	12.76	12.34	11.94	11.56	11.18	10.82	10.47	10.13	9.80
6	12.44	12.04	11.65	11.27	10.91	10.56	10.22	9.89	9.57
7	12.13	11.74	11.36	11.00	10.65	10.31	9.98	9.66	9.35
8	11.83	11.46	11.09	10.74	10.40	10.07	9.75	9.44	9.14
9	11.55	11.18	10.83	10.49	10.16	9.84	9.53	9.23	8.94
10	11.28	10.92	10.58	10.25	9.93	9.62	9.32	9.03	8.75
11	11.02	10.67	10.34	10.02	9.71	9.41	9.12	8.83	8.56
12	10.77	10.43	10.11	9.80	9.50	9.21	8.92	8.65	8.38
13	10.52	10.20	9.89	9.59	9.29	9.01	8.73	8.47	8.21
14	10.29	9.98	9.68	9.38	9.10	8.82	8.55	8.29	8.04
15	10.07	9.77	9.47	9.19	8.91	8.64	8.38	8.13	7.88
16	9.86	9.56	9.28	9.00	8.73	8.47	8.21	7.97	7.73
17	9.65	9.36	9.09	8.82	8.55	8.30	8.05	7.81	7.58
18	9.45	9.17	8.90	8.64	8.38	8.14	7.90	7.66	7.44
19	9.26	8.99	8.73	8.47	8.22	7.98	7.75	7.52	7.30
20	9.08	8.81	8.56	8.31	8.06	7.83	7.60	7.38	7.17
21	8.90	8.64	8.39	8.15	7.91	7.68	7.46	7.25	7.04
22	8.73	8.48	8.23	8.00	7.77	7.54	7.33	7.12	6.91
23	8.56	8.32	8.08	7.85	7.63	7.41	7.20	6.99	6.79
24	8.40	8.16	7.93	7.71e	7.49	7.28	7.07	6.87	6.68
25	8.24	8.01	7.79	7.57	7.36	7.15	6.95	6.75	6.56
26	8.09	7.87	7.65	7.44	7.23	7.03	6.83	6.64	6.46
27	7.95	7.73	7.51	7.31	7.10	6.91	6.72	6.53	6.35
28	7.81	7.59	7.38	7.18	6.98	6.79	6.61	6.42	6.25
29	7.67	7.46	7.26	7.06	6.87	6.68	6.50	6.32	6.15
30	7.54	7.33	7.14	6.94	6.75	6.57	6.39	6.22	6.05
31	7.41	7.21	7.02	6.83	6.64	6.47	6.29	6.12	5.96
32	7.29	7.09	6.90	6.72	6.54	6.36	6.19	6.03	5.87
33	7.17	6.98	6.79	6.61	6.43	6.26	6.10	5.94	5.78
34	7.05	6.86	6.68	6.51	6.33	6.17	6.01	5.85	5.69
35	6.93	6.75	6.58	6.40	6.24	6.07	5.91	5.76	5.61
36	6.82	6.65	6.47	6.31	6.14	5.98	5.83	5.68	5.53
37	6.72	6.54	6.37	6.21	6.05	5.89	5.74	5.59	5.45
38	6.61	6.44	6.28	6.12	5.96	5.81	5.66	5.51	5.37
39	6.51	6.34	6.18	6.02	5.87	5.72	5.58	5.44	5.30
40	6.41	6.25	6.09	5.94	5.79	5.64	5.50	5.36	5.22

tures are provided in table 6. Notice that the concentration of dissolved oxygen at saturation declines markedly as water temperature increases. The concentration of dissolved oxygen at saturation also declines with increasing salinity, but this effect is not great over the salinity range for freshwater aquaculture. At high salinity, water holds considerably less dissolved oxygen than at low salinity. The concentration of dissolved oxygen at saturation decreases with decreasing barometric (atmospheric) pressure. Variation in barometric pressure at a given locality may be ignored, but variations in barometric pressure resulting from elevation must be taken into account when data from table 6 is used.

If the pressure at a particular site is known–even if the elevation of the site is not known–the correction of data in table 6 may be made with the equation:

$$DO_c = DO_t \left[\frac{BP}{760}\right]$$

where DO_c = corrected dissolved oxygen concentration at saturation (mg/liter)

DO_t = concentration at saturation from table 6

BP = local barometric pressure.

Where barometric pressure is unknown, the approximate change in pressure with increasing elevation is as follows: 0 to 600 meters — 4% decrease in barometric pressure per 300 meters; 600 to 1,500 meters — 3% decrease in barometric pressure per 300 meters; 1,500 to 3,000 meters — 2.5% decrease in barometric pressure per 300 meters. For example, suppose the elevation at a pond surface is 250 meters and the water temperature is 30°C. The approximate barometric pressure will be:

$$760\text{mm} - 760\left[\frac{250\text{m} \times 0.03}{300}\right] = 741\text{mm}.$$

At 30°C and 760 millimeters barometric pressure, the dissolved oxygen concentration at saturation is 7.54 milligrams per liter (table 6). The actual concentration of dissolved oxygen at saturation for the pond surface is:

$$DO_c = 7.54\left[\frac{741}{760}\right] = 7.35 \text{ mg/l}.$$

Pressure at a point in water is influenced by the depth of the point beneath the water surface. The weight (pressure) of water above the point is called the hydrostatic pressure, and the total pressure at the point is hydrostatic pressure plus barometric pressure. The solubility of dissolved oxygen at saturation at the point is a function of total pressure. Thus, the solubility of dissolved oxygen at saturation increases with increasing water depth. The approximate increase in pressure with increasing depth is 73.42 milliliters of mercury per meter. Thus, if the barometric pressure is 760 millimeters and depth is one meter, the total pressure is 760 + 73.42 = 833.42 millimeters. Aquaculture ponds are shallow and the effect of depth on the solubility of dissolved oxygen at saturation normally is ignored.

Plants growing in pond water produce oxygen in photosynthesis, and during daylight, plants may produce oxygen so fast that dissolved oxygen concentrations in water rise above saturation. Water containing more dissolved oxygen than expected for the existing barometric pressure and water temperature is said to be supersaturated with dissolved oxygen. Water also may contain less dissolved oxygen than expected at saturation for prevailing conditions. Respiration by organisms in ponds may cause dissolved oxygen levels to decline; dissolved oxygen typically declines below saturation at night.

When water is below saturation with dissolved oxygen, there is a net movement of oxygen molecules from air to water. At saturation with dissolved oxygen, the number of oxygen molecules leaving the water equals the number entering; there is no net movement of oxygen molecules. Net movement of oxygen molecules from water to air occurs when water is supersaturated with dissolved oxygen. The larger the difference between the pressure of oxygen in water and air, the greater is the net exchange of oxygen molecules.

The degree of saturation of water with dissolved oxygen frequently is expressed as percentage saturation. The equation for estimating percentage saturation is:

$$\%\ \text{Saturation} = \frac{\text{DO concentration in water}}{\text{DO concentration at saturation}} \times 100.$$

For example, if the barometric pressure is 760 millimeters, the water temperature is 20°C, and the dissolved oxygen concentration is 11.0 milligrams per liter, the percentage saturation is (11.0 ÷ 9.08) x 100 = 121.1%.

Effects on Culture Species

The influence of dissolved oxygen concentrations on pond aquaculture species is summarized in table 7. Concentrations of dissolved oxygen can fall so low that creatures in ponds die. However, adverse effects of low dissolved oxygen more often are expressed as reduced growth and greater susceptibility to disease. In ponds with chronically low dissolved oxygen concentrations, creatures will eat less and they will not convert food to flesh as efficiently as in ponds with normal dissolved oxygen concentrations.

Gas supersaturation also can be harmful to culture species. Gas bubble trauma results from bubbles of gases forming in the blood. This may result when creatures ini-

TABLE 7. INFLUENCE OF DISSOLVED OXYGEN CONCENTRATIONS ON POND AQUACULTURE SPECIES

Dissolved oxygen concentration	Effect
Less than 1 or 2 mg/liter	Lethal if exposure lasts more than a few hours
2-5 mg/liter	Growth will be slow if exposure to low dissolved oxygen is continuous
5 mg/liter–saturation	Best condition for good growth
Above saturation	Can be harmful if supersaturated conditions exist throughout pond volume. Normally, there is no problem

tially in gas-supersaturated water are suddenly exposed to water of much lower gas concentration. The blood was supersaturated with gas under supersaturated conditions, but at a lower concentration of dissolved gas, the supersaturating gases in the blood form bubbles. These bubbles have adverse effects on various organs and physiological processes. The most common causes of gas supersaturation are entrainment of air by water falling over high dams, air entrainment through leaks on suction sides of pumps, and sudden transfer of creatures from cool water to warmer water. Photosynthesis can cause supersaturation of pond surface waters with dissolved oxygen, but this is usually not harmful to pond species. They can move to greater depths where dissolved oxygen concentrations are lower and the dissolved oxygen concentration at saturation is greater.

Plankton and Dissolved Oxygen

Light passing through pond water is quenched rapidly, and the rate of quenching increases as the amount of particulate matter (turbidity) in the water increases. As a result, photosynthesis occurs most rapidly in the surface layer of water, and dissolved oxygen concentrations decline with depth. Plankton blooms reduce light penetration, and the amount of light available for photosynthesis at a given depth is proportional to the amount of plankton. In ponds with a lot of plankton, dissolved oxygen concentrations may fall to 0 milligrams per liter at depths of 1.5 or two meters (figure 7). Because of this, it is best to use relatively shallow ponds (one to 1.5 meters) for aquaculture where climatic condition and water supply permits. Of course, in areas with a long dry season, it may be impossible to maintain adequate water depth in shallow ponds.

Concentrations of dissolved oxygen exhibit a daily cycle. The lowest concentrations of dissolved oxygen occur about dawn. During daylight, photosynthesis causes dissolved oxygen concentrations to increase, and maximum dissolved oxygen concentrations are reached in the afternoon. During the night, photosynthesis ceases but continuing use of oxygen by pond organisms causes dissolved oxygen concentrations to decline. The daily cycle in dissolved oxygen is most pronounced in ponds with heavy phytoplankton blooms (figure 8). The influence of the daily cycle of dissolved oxygen on growth of aquaculture species is poorly understood, but most workers feel that good growth can be achieved as long as the dissolved oxygen concentration does not fall below 25 or 30% of saturation during the night and does not remain at this low level for more than one or two hours.

Cloudy weather can influence dissolved oxygen concentrations as illustrated in figure 9. This results because cloudy weather reduces the rate of photosynthesis through light limitation, but it has little or no effect on respiration. The influence of cloudy weather is more pronounced in a pond with a heavy phytoplankton bloom than in a pond with less phytoplankton.

In summary, as fertilization or feeding rates are

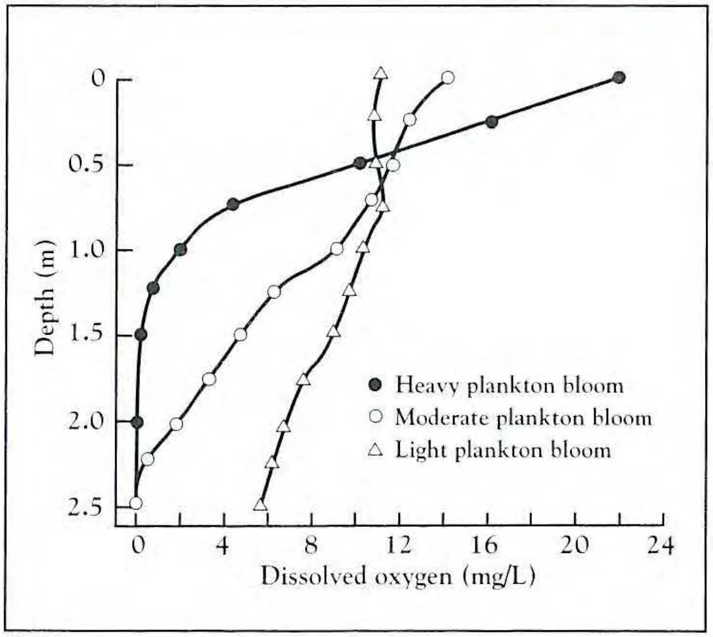

Figure 7. Influence of depth on dissolved oxygen concentrations in ponds with different amounts of plankton.

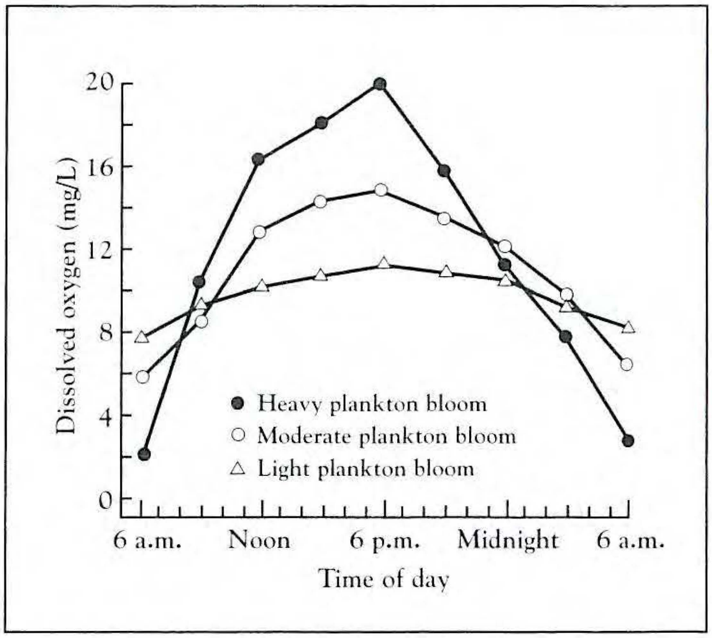

Figure 8. Effect of time of day and plankton density on concentrations of dissolved oxygen in surface water.

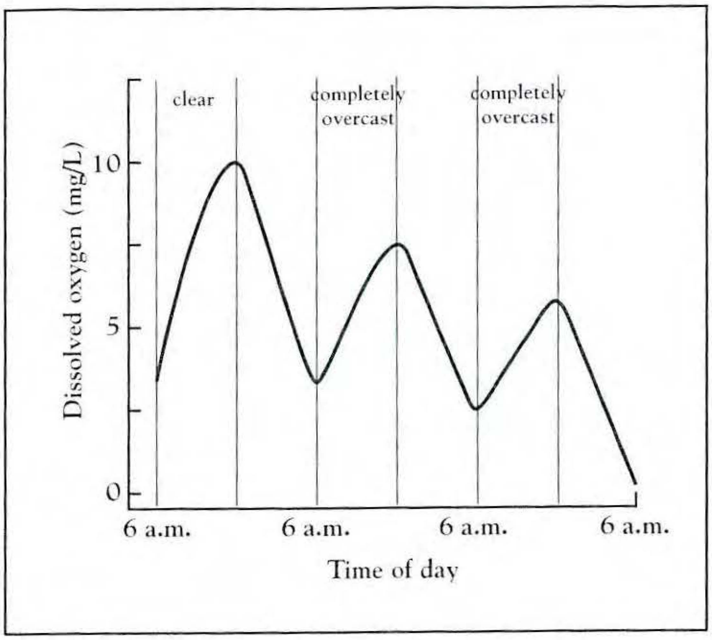

Figure 9. Effect of cloudy weather on dissolved oxygen concentrations in a pond.

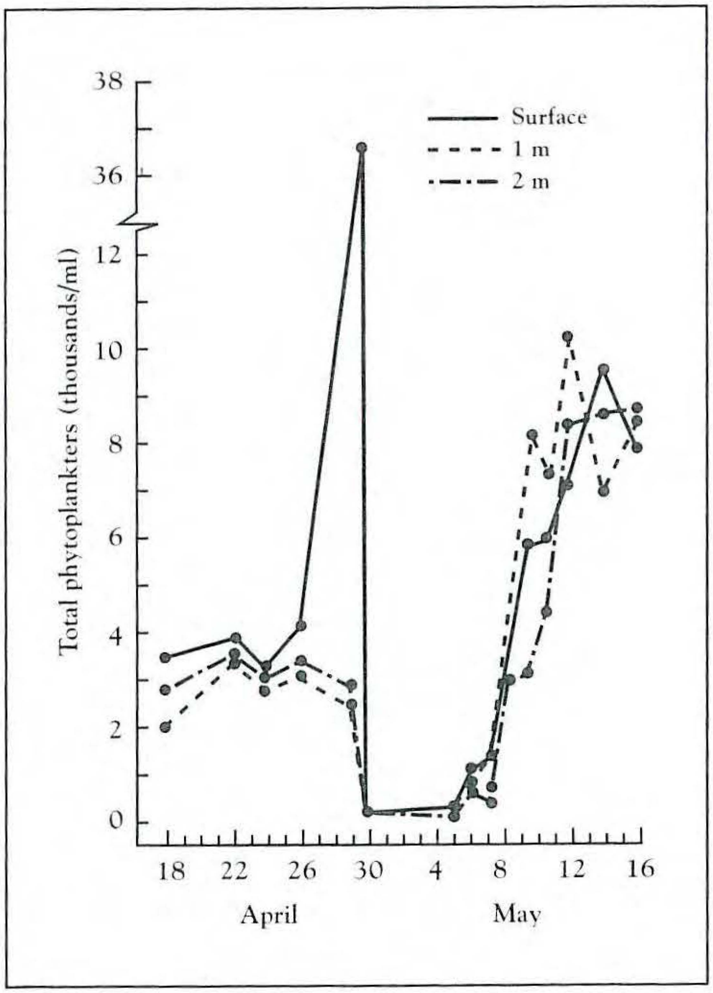

Figure 10. Changes in phytoplankton abundance before, during, and after a massive phytoplankton die-off in a pond.

increased in aquaculture ponds, phytoplankton abundance increases. This permits greater aquacultural production, but it also causes dissolved oxygen concentrations to fluctuate widely between day and night and to decrease with depth. If fertilization or feeding rates are too high, phytoplankton blooms will become so dense that growth of culture species will decline or the culture species will die because of low dissolved oxygen concentrations. The aquaculturist must adjust the fertilization or feeding rates so that there is both adequate plankton and dissolved oxygen for good production of fish or other species. Because of differences in responses of individual ponds to fertilization and feeding, it is not possible to recommend a single, maximum safe fertilizer or feed application rate and schedule suitable for all ponds. It is essential that the pond manager observe each pond carefully and adjust fertilizer and feed applications to fit pond conditions.

Phytoplankton in ponds may suddenly die and decompose causing a dissolved oxygen depletion (8). An example of a phytoplankton die-off is shown in figure 10, and the influence of the die-off on dissolved oxygen concentrations is illustrated in figure 11. The dissolved oxygen concentrations did not return to normal until a new phytoplankton bloom was established. Most phytoplankton die-offs involve species of blue-green algae. During calm weather, blue-green algae often form scums at pond surfaces. Intense sunlight may result in sudden death of algae in this scum. Blue-green algae have high concentrations of

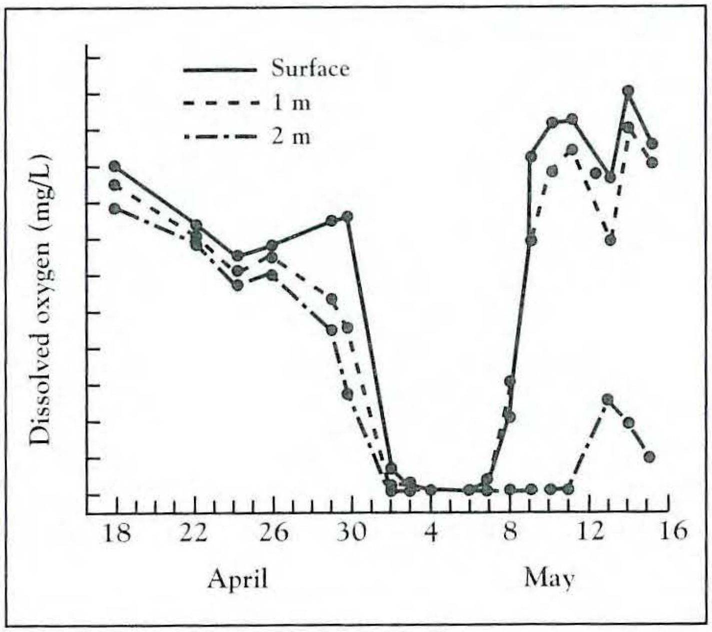

Figure 11. Dissolved oxygen concentrations before, during, and after a massive phytoplankton die-off in a pond.

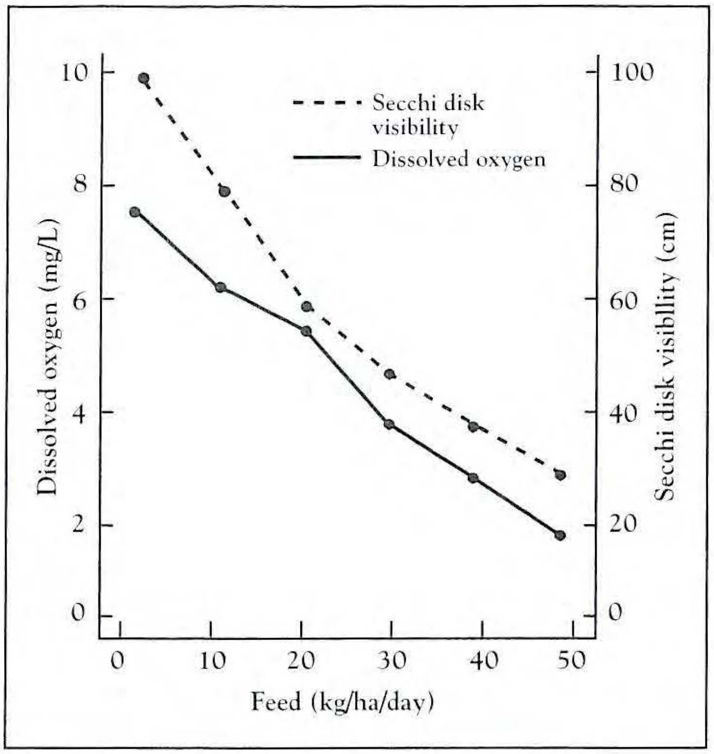

Figure 12. Effect of feeding rate on dissolved oxygen concentrations at dawn and on Secchi disk visibilities in ponds.

nitrogen in their tissue, so they decompose rapidly.

Mats of filamentous algae which develop on pond bottoms may, under certain conditions, float to the surface of a pond and die. This phenomenon also can deplete dissolved oxygen.

Bottom Sediment and Dissolved Oxygen

Although plankton abundance usually is the dominant factor in dissolved oxygen dynamics in aquaculture ponds, the bottom sediments also consume dissolved oxygen. Bottom sediments, especially in old ponds where large amounts of organically-enriched sediment have accumulated, may exert large oxygen demands. There has been little research on dissolved oxygen consumption rates by pond soils, but there is evidence that respiration by the benthic community can easily remove two to three milligrams per liter of dissolved oxygen from the pond water in 24 hours.

Feeding and Dissolved Oxygen

Phytoplankton abundance is controlled by nutrient supply, and dissolved oxygen concentrations are regulated to a large extent by phytoplankton abundance. Feed applied for aquaculture species results in pollution of pond waters by organic and inorganic metabolic wastes. Uneaten feed also decomposes, releasing nutrients into the water. Consequently, phytoplankton abundance and problems with low dissolved oxygen increase as a function of increasing feeding rate (figure 12). These data suggest that feeding rates above 40 or 50 kilograms per hectare per day will result in unacceptably low dissolved oxygen. Higher feeding rates may be used in ponds if mechanical aeration is applied. Tilapia are more tolerant to low dissolved oxygen than most other aquaculture species, and somewhat higher feeding rates are possible without mechanical aeration.

The feed conversion ratio is determined as the quantity of feed applied divided by the net production (creatures harvested minus initial stocking weight). For example, suppose that a one-hectare pond had a net production of 5,000 kilograms of fish and 9,000 kilograms of feed had been applied. The feed conversion ratio is:

$$\frac{9{,}000 \text{ kg feed}}{5{,}000 \text{ kg fish}} = 1.80.$$

A low feed conversion ratio indicates greater efficiency than a high value does. With good management practices, feed conversion ratios of 1.5 to 2.0 may be achieved with most species of fish and crustaceans.

Commercial aquaculture feeds do not usually contain more than 5 or 10% moisture, but most aquatic creatures are about 75% water. Dry matter feed conversion ratios are much larger than the feed conversion ratios computed by dividing live net production weight into amount of feed. In channel catfish culture, 1,800 kilograms of feed might produce a net of 1,000 kilograms of live fish. The feed is about 92% dry matter, so the input of dry matter is 1,656 kilograms. The fish are about 25% dry matter, so they contain about 250 kilograms of dry matter. The dry matter feed conversion ratio is 6.62. Thus, 5.62 kilograms of dry weight equivalent of metabolic wastes and uneaten feed reach the pond during the production of 1,000 kilograms of live fish. This dry matter contains nutrients that are released to the pond water by fish respiration and excretion and by microbial decomposition of uneaten feed and fish feces. These nutrients stimulate phytoplankton productivity, and additional organic matter is formed within the pond ecosystem by algae. Thus, as feeding rates increase, the load of wastes and nutrients to the pond water increases. In other words, the pond becomes more eutrophic or polluted as feeding rates increase. If feeding rates become too high, fish will be stressed by impaired water quality. The first water quality problem to develop usually is low dissolved oxygen concentration in the early morning. This problem can be solved by mechanical aeration, but if feeding rates are increased enough, ammonia concentrations may become high enough to cause toxicity. Although this example is for channel catfish, the principles illustrated apply equally well to other pond culture species.

One of the effects of overfeeding in fish and crustacean ponds is to increase the feed conversion ratio. As feeding rate increases, dissolved oxygen concentrations during the night decline. Chronically low dissolved oxygen concentrations have an adverse effect on the appetite and metabolism of fish and crustaceans, and feed conversion values tend to increase drastically if feeding rates are increased to a level where dissolved oxygen concentrations fall below two or three milligrams per liter each night.

NITROGEN

The nitrogen cycle is presented in figure 13. Nitrogen may enter ponds from the atmosphere in molecular form (N_2), and some molecular nitrogen can be fixed in organic compounds by blue-green algae and bacteria. Rain falling into ponds contains nitrate, and various forms of nitrogen may enter ponds via the water supply. Inorganic nitrogen may be added in fertilizer and organic nitrogen in manure or feed. In the pond, nitrogen undergoes many transformations through biological activity. These activities will be discussed below.

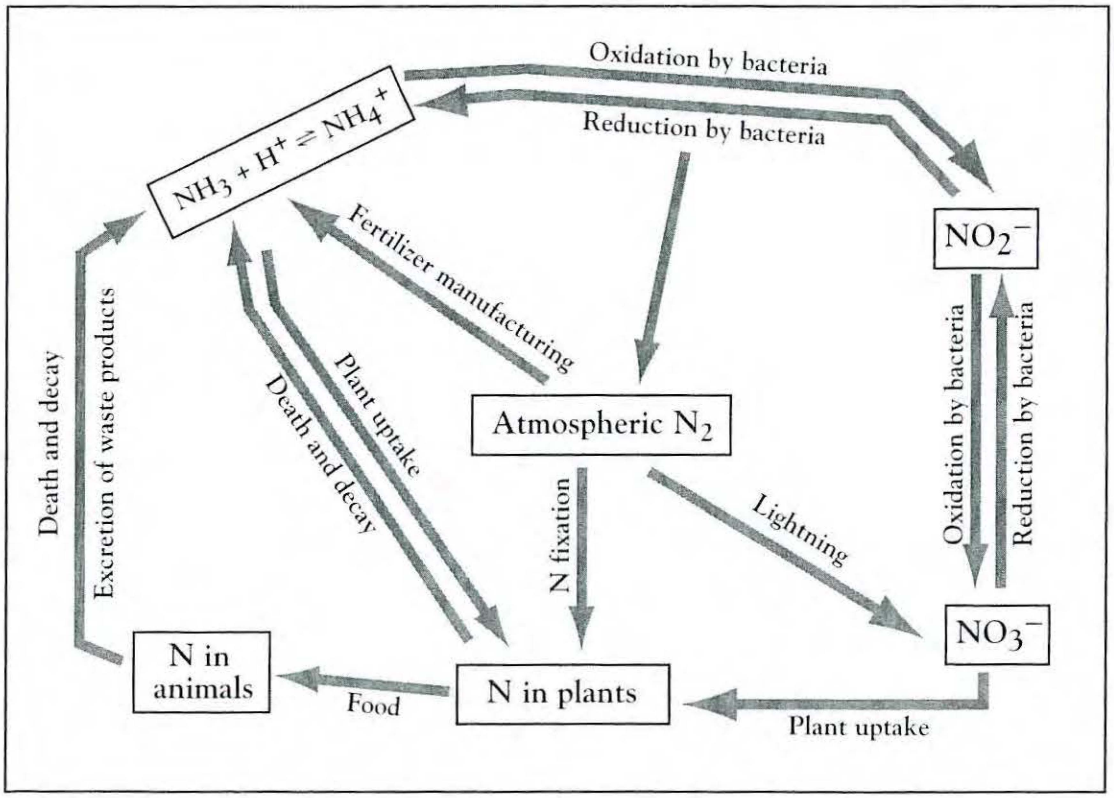

Figure 13. Nitrogen cycle a in fish pond.

Plant Uptake

All plants can use nitrate and ammonium nitrogen, and as mentioned above, blue-green algae can fix elemental nitrogen. Phytoplankton can absorb large amounts of ammonium, and they are a dominant factor controlling the concentration of ammonia nitrogen in pond waters. In the plant, the nitrogen is reduced to ammonia and combined with organic carbon to form amino acids. These amino acids are then combined to form protein. Plants may be consumed by creatures and they may die and become detritus.

Use by Creatures

Creatures eat plants, detritus, other creatures, or some combination of these. Creatures need their nitrogen in the form of amino acids of protein. When aquatic creatures take in food, part of the organic nitrogen in the food is assimilated and converted to animal protein. The remainder is expelled as organic nitrogen in feces or excreted as ammonia. When aquatic creatures are harvested, the nitrogen that they contain is removed from the pond.

Fate of Nitrogen in Organic Matter

Some of the dead organic matter (detritus or smaller particles of material in soil and water) is consumed directly by creatures. Ultimately, most dead organic matter becomes substrate (food) for microbial organisms (bacteria, actinomycetes, and fungi). Factors affecting the rate of organic matter decomposition are temperature, pH, oxygen availability, and the nature of the organic matter. Microorganisms capable of degrading organic matter are present in all ponds, and their abundance will increase when organic matter is increased. Microbial decomposition increases with temperature up to about 40°C, and within this temperature range, a 10°C increase in temperature will cause the rate of decomposition to roughly double. Degradation of organic matter proceeds most rapidly at pH 7 to 8. Therefore, in acidic ponds, organic matter tends to accumulate unless lime is applied to improve pH. Organic matter that has a high concentration of nitrogen relative to its concentration of carbon (low C/N ratio) will decompose faster than a material with a high C/N ratio. Additionally, more nitrogen will be released to the environment as ammonia by microorganisms of decay when a substance with a low C/N ratio decomposes. If an organic material is very low in nitrogen, there will not be enough nitrogen in it to effect complete decomposition by microorganisms. In this event, bacteria and other microorganisms of decay will remove nitrate and ammonia from pond water for use in decomposition of organic matter. Removal of nitrogen from the environment by microorganisms degrading nitrogen-deficient organic matter is called immobilization of nitrogen.

Nitrification

The ammonia released to the pond water by decomposition may be used again by plants, or it may be nitrified to nitrate by chemoautrophic bacteria. Oxidation of ammonium to nitrite by bacteria of the genus *Nitrosomonas* is the first step in nitrification:

$$NH_4 + 1\,1/2\ O_2 \rightarrow NO_2^- + 2H^+ + H_2O.$$

In the second step, nitrite is oxidized to nitrate by bacteria of the genus *Nitrobacter*:

$$NO_2^- + 1/2\ O_2 \rightarrow NO_3.$$

These bacteria use the energy released in the oxidation of ammonium and nitrite to reduce carbon dioxide to organic carbon. In other words, these organisms can produce organic matter by a non-photosynthetic pathway. Of course, the amount of organic matter produced by nitrification in ponds is minute compared to the amount produced by photosynthesis. Nitrification is important in reducing the concentration of ammonia in pond waters, and this is beneficial to aquaculture because ammonia is potentially toxic. However, nitrification also has adverse effects on water quality. It is a significant source of acidity in ponds because hydrogen ions (H^+) are released, and it exerts an oxygen demand because oxygen is required to oxidize ammonia.

Denitrification

In the absence of oxygen, many microorganisms can use nitrate or other oxidized nitrogen compounds as sources of oxygen and as electron and hydrogen acceptors in respiration. Thus, organic matter decomposition can continue in the absence of dissolved oxygen. This heterotrophic process is termed denitrification because gaseous forms of nitrogen are released as metabolites and lost from the pond. For example, nitrate can be reduced to nitrite, nitrite can then be reduced to nitrous oxide, and, finally, nitrous oxide can be reduced to nitrogen gas. Physiologically, the process can best be defined as nitrate respiration. Denitrification occurs in pond soils where dissolved oxygen concentrations are low. Denitrification is the major loss of nitrogen from ponds, and the summary equation is:

$$6NO_3 + 5CH_3OH \rightarrow 5CO_2 + 3N_2 + 7H_2O + 6OH^-.$$

In the above summary equation for denitrification, methanol has been used as an organic carbon source. Of course, many other organic carbon compounds can be used by denitrifying bacteria.

Ammonia Volatilization

Some ammonia is lost from pond water directly to the air when the pressure of ammonia gas in water exceeds the pressure of ammonia in the air. This process is most important at pH 9 and above. The importance of ammonia volatilization in the nitrogen balance of ponds is poorly understood, but it is not thought to be a significant factor in most ponds because pH is not great enough to favor rapid loss of ammonia to the air.

Summary

Because of the high rate of internal nitrogen recycling in pond ecosystems and the fixation of nitrogen by blue-green algae and bacteria, it usually is not necessary to apply large amounts of nitrogen to ponds in fertilizers. In ponds, large amounts of nitrogen enter ponds in feeds, and substantial quantities of ammonia enter water in metabolic wastes of the culture species and from decomposition of uneaten feed and feces. Therefore, a major concern in intensive aquaculture is the accumulation of excessive concentrations of ammonia in pond water.

PHOSPHORUS

Ambient phosphorus concentrations in pond water are usually quite low. Phosphorus is introduced into ponds in fertilizers to stimulate phytoplankton blooms, enhance the abundance of natural food organisms, and promote greater aquacultural production. In ponds with feeding, a portion of the feed phosphorus is not assimilated by the culture species and enters ponds to stimulate phytoplankton productivity.

Fate of Phosphorus in Ponds

The phosphorus cycle in a pond is illustrated in figure 14. When phosphate is added in a chemical fertilizer, a high concentration of phosphate will remain in the water for only a few hours or days. However, the concentration will quickly decline to the pre-treatment level. Some phosphorus loss from the water may be attributed to uptake by plants and bacteria. Heavy phytoplankton blooms can absorb large amounts of phosphorus. Much phosphorus will, however, be adsorbed by the pond soil. Even that phosphorus initially absorbed by the phytoplankton will eventually be mineralized from organic matter and enter the pond soil.

The amount of phosphorus entering ponds from natural sources, including release from the soil, is usually rather small even in highly productive ponds. Phosphorus must be applied in fertilizers to maintain productivity. Phosphorus in manures is released when manure is degraded by bacteria. The amount of phosphorus harvested in aquatic creatures usually represents less than one-third of the phosphorus added to ponds. Nevertheless, animal biomass harvested from ponds is the greatest loss of phosphorus from an aquaculture ecosystem. Most added phosphorus remains in the pond as insoluble phosphate compounds in the soil. Unfortunately, the soil phosphorus is not highly available to non-rooted plants in the pond.

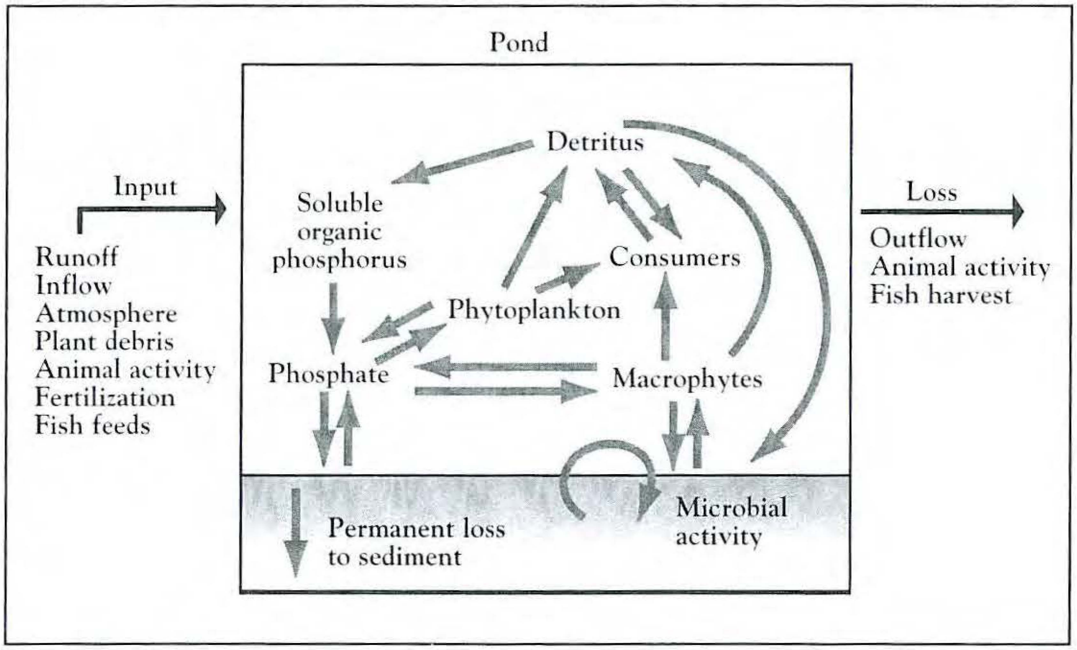

Figure 14. The phosphorus cycle in a fish pond.

Reactions with Muds

Inorganic phosphorus in soils or muds occurs as calcium, iron, and aluminum phosphates. In acidic soils, aluminum ion occurs at fairly high concentration and reacts with phosphate to form highly insoluble aluminum phosphate according to the general reaction:

$$Al^{3+} + H_2PO_4^- = AlPO_4 + 2H^+.$$

At the same pH, there are several orders of magnitude more aluminum ion than ferric iron in aerobic mud. Therefore, phosphate first reacts with aluminum, but the existence of iron phosphates in mud suggests that some aluminum phosphate is transformed to iron phosphate. When muds become anaerobic, iron phosphates dissolve, and anaerobic water at the pond bottom may be high in phosphate. Nevertheless, when the water becomes aerobic again, iron phosphate reprecipitates. As pond soil pH increases, the concentration of aluminum ion decreases so that less phosphate precipitates as aluminum phosphate. Somewhere between pH 6 and 7, the precipitation of aluminum phosphate ceases to be the dominant factor removing phosphate from the water. As pond soil increases in pH, the concentration of calcium increases and phosphorus precipitates as calcium phosphate. Over time, calcium phosphate is transformed to a highly insoluble mineral apatite (rock phosphate). Where pH and calcium concentration are high, apatite may precipitate directly from the water. Muds also contain organic phosphorus. Microbial decomposition of organic matter will release phosphate which will participate in reactions with iron, aluminum, and calcium.

Phytoplankton can quickly absorb phosphate from the water, so a large proportion of the phosphorus applied to a pond may enter phytoplankton cells and promote growth. Phytoplankton cells may be consumed by aquatic creatures, but most die and settle to the bottom. Studies have shown that about 70% of the phosphorus added to ponds in fertilizers or feeds eventually finds its way into the mud. Pond bottom soil phosphorus is in equilibrium with phosphorus in pond waters, but in spite of this, the phosphorus concentrations in water are low. Thus, pond sediment tends to be a sink rather than a source for phosphorus *(13)*.

Summary

Phosphate must be supplied at frequent intervals to fertilized ponds in order to maintain a desirable abundance of phytoplankton. In ponds with feeding, decomposition of uneaten feed and feces continuously supplies phosphorus to the water. Uptake by the soil is a desirable phenomenon in ponds with feeding because it controls the phosphorus concentration in water and is a major factor in the prevention of excessive phytoplankton abundance. Of course, if feeding rates are high enough, residual phosphorus concentrations in water may become great enough to cause troublesome phytoplankton blooms in spite of soil uptake.

POND SOIL

Soils play several important roles in aquaculture ponds. The bottom soils and earth-fill embankments of ponds serve as the basin in which pond water stands. Bottom soils store and release both nutrients and organic matter, and they provide a medium for growth of benthic creatures and plants and associated bacteria. These organisms may provide food for other organisms/fish, and they also recycle nutrients and degrade organic matter. Some culture species feed on the pond bottom, and some build nests and lay eggs on the bottom.

Pond soils are derived from terrestrial soils. However, conditions in pond bottoms are different from conditions in surface, terrestrial soils. Organic matter added to or produced in ponds, suspended solids entering ponds in runoff, and particles re-suspended from the pond bottom by water currents are continually deposited on the pond bottom to form a layer of sediment. Dissolved oxygen concentrations are usually low in pore water of bottom sediment, and organic matter decomposition progresses at a slower rate than in terrestrial soil. Also, carbonates, ferric hydroxide, and phosphate commonly precipitate from pond water into sediment. Pond bottoms tend to be the final recipient of residues of substances that are added to or produced in the pond. A detailed discussion of pond soils can be found in Boyd *(3)*.

TEXTURE

The texture of a soil refers to the proportion of gravel, sand, silt, and clay particles in the soil. Particle size analysis of an agricultural soil provides the percentages of sand, silt, and clay from which a soil texture name–for example, sandy loam, clayey loam, etc.–may be assigned with the aid of a soil triangle (see any general soil text). In studies of pond soils, however, the agricultural soil classification scheme has little value. On the other hand, it is good to know how much clay is in a pond soil, for the clay is the reactive fraction. Soil also contains organic matter, and organic matter, like clay, is highly reactive.

There is a common misconception that pond soils should have a high clay content to prevent seepage. Soils for making pond bottoms and levees should contain some clay, but 10 to 20% clay content usually is enough provided the soil contains particles of several size fractions. Soils containing 25% or more of clay particles often are very sticky and difficult to spread and to compact during construction. Levees made from such materials may have a tendency to slip. Also, drying and other treatments of heavy clay bottom soils between crops often are difficult.

CATION EXCHANGE

Colloidal particles of organic matter and clay minerals in pond soil have negative charges and attract swarms of cations (positively-charged ions). An equilibrium exists between concentrations of cations in water surrounding soil particles and amounts of cations adsorbed on soil particles (figure 15). If a large amount of potassium ion is added to the water of the equilibrium system illustrated in figure 15, the increased potassium ion concentration in the water will disrupt the equilibrium. In order to re-establish equilibrium conditions, potassium ion will replace some of the ions adsorbed on the soil particles, and the concentrations of all ions in the water will increase.

Cations on soil colloids and in surrounding water are known as exchangeable cations and the sites of adsorption on colloids are called exchange sites. Some cations are held more tightly than others to colloids. In general, the order of

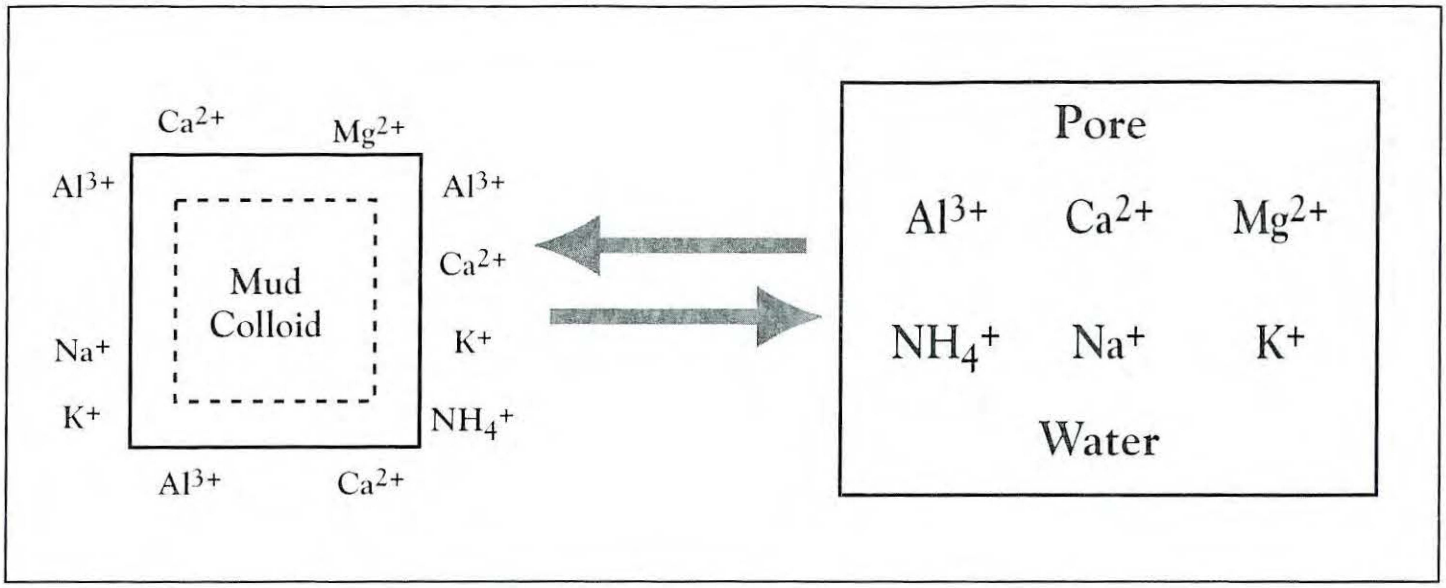

Figure 15. Exchange of cations between soil particles and water.

attraction between cations and colloids increases with increasing valence of the cation. That is, aluminum ion (+3 valence) is held tighter than calcium ion (+2 valence), and calcium ion is attracted more strongly than potassium ion (+1 valence).

The quantity of cations which can be adsorbed on soils is called the cation exchange capacity (CEC). The CEC is measured in milliequivalents of cations per 100 grams dry soil (meq/100 g). Clearly, the larger the CEC of a soil, the greater is the ability of the soil to exchange and hold ions. The CEC of pond muds ranges from less than 1 meq/100 g to more than 100 meq/100 g. The CEC increases as the percentage of clay, organic matter, or both increase. Some types of clays have greater exchange capacities than others. Bottom soils with CEC values of 10 to 40 meq/100 g seem to be best for aquaculture. The CEC is a natural property of soil that cannot normally be altered by pond treatments.

ACIDITY

The cations adsorbed on exchange sites in soils are acidic (aluminum ion, ferric ion, and hydrogen ion) or basic (calcium ion, magnesium ion, potassium ion, sodium ion, and ammonium ion). The fraction of the total exchange capacity occupied by acidic ions is called the base unsaturation. In most soils, there will be small amounts of hydrogen ions or ferric ions on exchange sites. The primary acidic ion is aluminum ion.

The acidic reaction of aluminum may be visualized as follows:

$$\text{Al–Soil} = \text{Al}^{3+} + 3\text{H}_2\text{O} = \text{Al(OH)}_3 + 3\text{H}^+.$$

As the base unsaturation of a soil increases, the amount of aluminum ion available to react with water and form hydrogen ion increases. Therefore, soil pH decreases with increasing base unsaturation.

The way in which lime neutralizes acidity in mud is illustrated in figure 16. The calcium carbonate reacts with hydrogen ions and neutralizes them. This lowers the concentration of hydrogen ions in solution and more aluminum ions are released from the soil. Aluminum ions released from the soil are replaced by calcium ions resulting from the neutralization of hydrogen ions by calcium carbonate. The end results are as follows: aluminum is removed from the soil and precipitated as aluminum hydroxide; calcium replaces the aluminum on the soil; the base unsaturation of the soil decreases; the pH of the soil increases.

Ponds sometimes are constructed in areas once covered by brackishwater tidal swamps and marshes. When rivers with a heavy sediment load emptied into the sea, sediment was deposited near the shore. After the deposits rose above mean low water level, vegetation became established. As deposition continued, the coast slowly accreted, and a swamp forest developed. In the swamp forest, tree roots trapped organic and inorganic debris, and decomposition of dense masses of organic debris resulted in anaerobic conditions. As a result, sulfur-reducing bacteria became abundant, and sulfide produced by the bacteria accumulated in pore spaces in sediment as hydrogen sulfide or combined with iron to form precipitates of iron sulfides. Iron sulfides underwent further chemical reaction to form iron disulfides that crystallized to form iron pyrite.

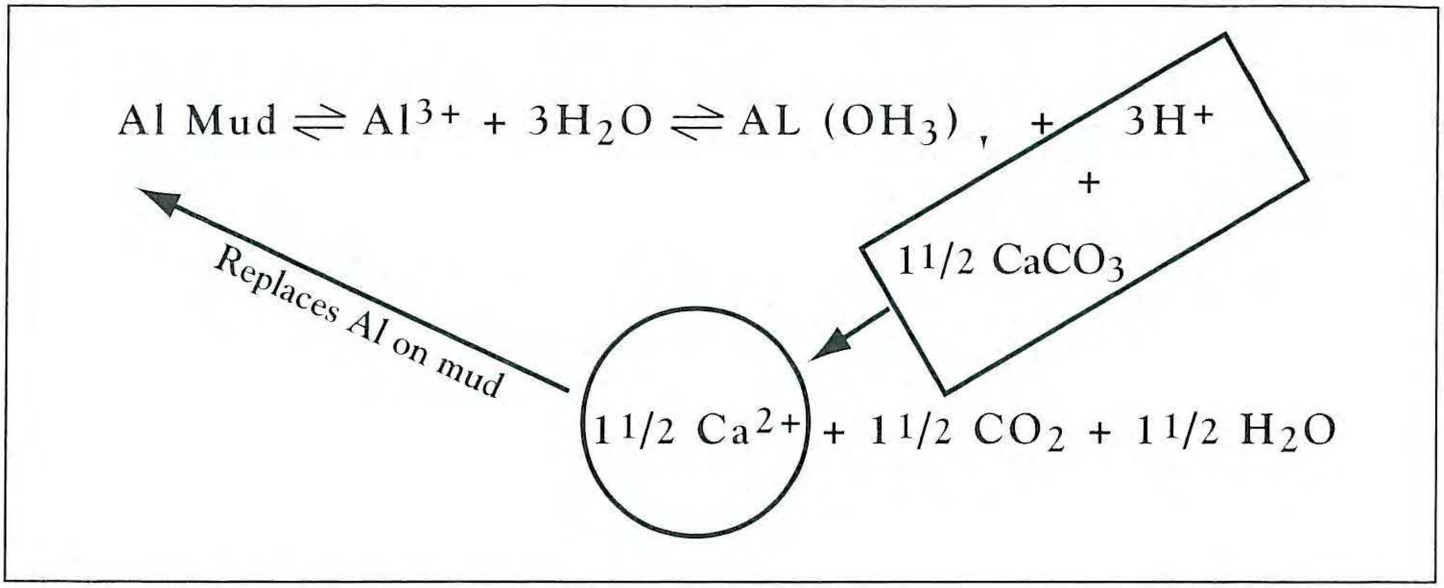

Figure 16. Neutralization of soil acidity by calcium carbonate.

As long as sediments containing pyrites are submerged and anaerobic, they remain reduced and change little. However, if they are drained and exposed to the air, oxidation results, and sulfuric acid is formed. The summary reaction for sulfuric acid formation from iron pyrite is:

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+.$$

The ferric hydroxide crystallizes as a reddish brown material in the sediment. After draining, a sediment containing pyrite is called a potential acid-sulfate soil or a "cat's clay."

When aerobic, acid-sulfate soil will have a pH below 4.0. The pH of acid-sulfate soils often will decrease as much as three units upon drying. Field identification of acid-sulfate soils can sometimes be made by the smell of hydrogen sulfide from disturbed soil, but the positive test is to measure pH before and after drying.

In ponds, the problem with acid-sulfate soils usually originates on the levees. Pond bottoms are usually flooded and anaerobic, so sulfuric acid does not form. However, levees dry and sulfuric acid formed during dry periods enters ponds in runoff after rains. Acidity on levees can be controlled by liming and establishing good cover with an acid-resistant species of grass. Fortunately, acid-sulfate soils are seldom a problem in freshwater ponds.

ORGANIC MATTER AND OXIDATION-REDUCTION

Organic matter accumulates at the soil water interface, and microbial activity is very intense in this surface layer. Because water does not move freely within sediment, microbial activity quickly reduces the oxygen concentration in the water within the sediment (pore water). Usually, aerobic conditions (presence of oxygen) will only occur in the upper few millimeters of sediment. As the oxygen concentration drops, the oxidation-reduction potential falls and various compounds are reduced. A substance is said to be reduced when one or more of the following events occur: it gains electrons, it gains hydrogen, it loses oxygen, or it becomes more electronegative. Some typical reductions that occur in pond mud include the following:

NO_3^- to NO_2^-
NO_2^- to NH_3
NO_2^- to N_2
NH_3 to N_2
Fe^{3+} to Fe^{2+}
Mn^{4+} to Mn^{2+}
SO_4^{2-} to H_2S
CO_2 to CH_4 (methane).

Under certain conditions these reductions may occur spontaneously in the absence of oxygen, but they usually are mediated by microorganisms. Under anaerobic conditions, the electrons and hydrogen ions formed as microorganisms degrade organic matter and cannot be reacted with oxygen. Therefore, the electrons and hydrogen ions are disposed of by reaction with oxidized inorganic substances. Of course, in the process the inorganic substance becomes reduced.

The degradation of organic matter in the mud causes the low dissolved oxygen condition, and the continued degradation of the organic matter results in the reduction of the inorganic substances. Thus, organic matter is the source of the reducing power that often leads to high concentrations of nitrite, ammonia, ferrous iron (Fe^{2+}), divalent manganese ion, hydrogen sulfide, and methane in pond muds. The absence of oxygen in sediment may slow down the rate of organic matter decomposition, but it does not halt decomposition. In fact, anaerobic conditions are normal in pond sediment, and aquaculture pond soils do not normally accumulate large amounts of organic matter unless inputs of organic matter are excessive. For example, in ponds with large input of manures, bottom soils may accumulate large amounts of organic matter. Nevertheless, if organic matter inputs to pond bottoms are so great that aerobic conditions cannot be maintained at the soil-water interface, culture creatures may be exposed to reduced and potentially toxic substances.

The iron reaction in water provides a means of determining if the surface layer of a mud is anaerobic. In the absence of oxygen, ferric iron (Fe^{3+}) is converted to ferrous iron (Fe^{2+}). Ferrous iron is black or dark gray in color. Therefore, when the surface of the mud is black, anaerobic conditions exist. When the surface is brown or the natural soil color, it suggests that oxygen is present. Of course, if you break through the aerobic surface layer of a mud, deeper layers will be anaerobic and black. It is highly desirable to maintain dissolved oxygen in the upper layer of sediment. Fish food organisms that live in mud require oxygen, and the presence of oxygen in the mud prevents formation of noxious reduced substances.

There is considerable interest in the amount of organic matter in pond sediment. However, evaluation of data on organic matter concentrations in pond soil is difficult. Because organic matter settles onto the bottom and is then decomposed and gradually mixed with deeper layers by physical and biological processes, the organic matter concentrations quickly decrease with sediment depth. The upper, flocculent layer of recently-deposited sediment may have an organic content of 50% or greater, but the organic content of the entire upper one to two cm layer seldom will exceed 10% except where ponds are built on soils with high concentrations of native organic matter (organic soils). When organic matter decomposes, the most readily decomposable material is degraded first and the more resistant material accumulates. Therefore, much of the organic residue in pond soils consists of material resistant to decay. The problem of excessive oxygen demand in bottom sediment is related to the rate of input of fresh, labile organic matter rather than to the amount of resistant, residual organic matter that has accumulated over time. At present, we do not have reliable methods for readily distinguishing between these two types of organic matter.

POND SOIL AND AQUACULTURAL PRODUCTION

Although relatively little is known about relationships between bottom soil properties and the production of aquaculture species, one study suggested soil properties have an important role in production (see table 8). In spite of the correlations between soil properties and fish production, good production of fish cannot be sustained without applications of manures, fertilizers, feeds, or some combination of these.

TABLE 8. THE EFFECTS OF BOTTOM SOIL PROPERTIES ON FISH PRODUCTION[1,2]

Variable	Range	Fish Production
pH	less than 5.5	low
	5.5 - 6.5	average
	6.5 - 7.5	optimum
	7.5 - 8.5	average
Available phosphorus	less than 3 ppm	low
	3 - 6 ppm	average
	more than 6 ppm	optimum
Organic nitrogen	less than 25 ppm	low
	25 - 50 ppm	average
	more than 75 ppm	optimum
Organic carbon	less than 0.5 %	low
	0.5 - 1.5 %	average
	1.5 - 2.5 %	optimum
	more than 2.5 %	declining

[1] Adapted from Banerjea *(1)*.

[2] Manures were being added to these ponds.

FERTILIZATION

Chemical Fertilizers

Inorganic fertilizers are substances which contain nitrogen, phosphorus, and potassium either alone or in combination. Examples of common fertilizer compounds are listed in table 9. When two or more of these materials are blended, the resulting mixture is called a mixed fertilizer. Fertilizers are classified by plant nutrient content; nitrogen is expressed as N, phosphorus as P_2O_5, and potassium as K_2O. Nitrogen is present in fertilizers as nitrate (NO_3^-), ammonium (NH_4^+), or urea [$(NH_2)_2CO$]; phosphorus is present as phosphate ($H_2PO_4^{2-}$); potassium occurs as potassium ion (K^+). Use of N, P_2O_5, and K_2O is traditional instead of descriptive; that is fertilizers do not contain N, P_2O_5, or K_2O as such.

A mixed fertilizer with a grade of 5-20-5 contains 5% N, 20% P_2O_5, and 5% K_2O . (This fertilizer is not necessarily the best for ponds, and it is being used simply for illustration.) A 100-kilogram quantity of mixed 5-20-5 fertilizer can be made of urea, superphosphate (TSP), and potassium chloride (KCl). In 100 kilograms of 5-20-5, there will be 5 kg N, 20 kg P_2O_5, and 5 kg K_2O. Necessary amounts of fertilizer compounds are:

5 kg N ÷ 0.45 kg N/kg urea = 11.1 kg urea
20 kg P_2O_5 ÷ 0.46 kg P_2O_5/kg TSP = 43.5 kg TSP
5 kg K_2O ÷ 0.60 kg K_2O/kg KCl = 8.3 kg KCl

Total fertilizer compounds = 62.9 kg
Filler (agricultural limestone) = 37.1 kg
Total = 100.0 kg

Fertilizer compounds must be diluted to 100 kilograms with filler so that the mixed fertilizer will have the proper N-P_2O_5-K_2O percentages. A material like agricultural limestone is added to the mixture of fertilizer compounds to dilute a fertilizer. In the example above, 37.1 kilograms of agricultural limestone would be added as filler.

When granular fertilizers are broadcast over pond surfaces, they settle to the bottom before dissolving completely. Phosphate in fertilizer settling to the bottom is adsorbed strongly by mud, and much of it never reaches the water. Liquid fertilizers are much more efficient than granular fertilizers, because they will not settle to the bottom. A good liquid fertilizer for use in ponds is ammonium polyphosphate (10-34-0 to 13-37-0), but other liquid fertilizers are equally suitable. If a liquid fertilizer cannot be purchased locally, a useful alternative is to dissolve a granular fertilizer in a container of water. Liquid fertilizers should be diluted with water and splashed over pond surfaces. Never pour liquid fertilizers directly into pond water, because they are heavier than water and will settle to the bottom. Recently, finely pulverized, instantly soluble fertilizers have been used as an alternative to liquid fertilizer. This finely pulverized material can be broadcast over pond surfaces, and because of its fine particle size, it will dissolve completely without settling to the bottom.

Controlled-release fertilizers are made by coating fertilizer particles with a polymer shell. Water enters the shell and dissolves the fertilizer, and the nutrients gradually seep out of the shell. These fertilizers are used mostly for horticulture applications, but there is evidence that they can be used in aquaculture. The only problem is that they are expensive as compared to other fertilizers used in aquaculture.

An alternative means of applying granular fertilizer to prevent it from contacting the soil is to pour it on an underwater platform so that water currents move the nutrients throughout the pond after they dissolve. Some managers also put fertilizer in porous bags and suspend these bags in ponds so that nutrients are released into the water as fertilizers dissolve. Either procedure prevents fertilizer granules from dissolving while in contact with pond bottom soils. Nevertheless, regardless of the type of fertilizer used or the technique used for applying it, the fertilizer nutrients will not remain in the pond water. A portion of the nutrients will be absorbed by plants and enter the culture species via the food chain. However, most of the plants will die and become organic matter in pond sediment and their nutrients will be

TABLE 9. APPROXIMATE GRADES OF COMMON COMMERCIAL FERTILIZERS

Substance	Percentage		
	N	P	K_2O
Urea	45	0	0
Calcium nitrate	15	0	0
Sodium nitrate	16	0	0
Ammonium nitrate	33	0	0
Ammonium sulfate	21	0	0
Superphosphate	0	16	0
Triple superphosphate	0	46	0
Monoammonium phosphate	11	48	0
Diammonium phosphate	18	48	0
Ammonium polyphosphate	10-13	34-37	0
Muriate of potash	0	0	60

recycled. The majority of the phosphorus added in fertilizer will be adsorbed by sediment and some of the fertilizer nitrogen will be denitrified. Nutrients also will be contained in water lost from ponds by seepage, overflow, and draining and in harvested fish or other aquatic creatures.

Extensive research has been conducted on freshwater pond fertilization. Application rates usually consist of two to eight kilograms per hectare of P_2O_5 alone, or applications of two to eight kilograms per hectare of both N and P_2O_5. One of the best fertilization programs for freshwater ponds consists of periodic applications of eight to 16 liters per hectare of a 10-34-0 liquid fertilizer. This dosage rate amounts to four to eight kilograms per hectare of P_2O_5 and one to two kilograms per hectare of N. A good granular fertilization program is 10 to 20 kilograms per hectare per application of diammonium phosphate (18-48-0). Fertilizer applications normally are made at two- to four-week intervals. Through the proper use of chemical fertilizers, aquacultural production can be increased two to 10 times above that possible in unfertilized ponds. Care must be taken not to apply excessive amounts of chemical fertilizers, for the resulting overabundance of phytoplankton can cause an oxygen depletion.

Less research has been done on fertilization of brackishwater ponds, but nitrogen appears to be more important in brackishwater than in freshwater. Therefore, fertilizers for brackishwater should contain more nitrogen than those for freshwater. Using more nitrogen does not mean that phosphorus is less important in brackishwater than in freshwater. A good fertilizer for brackishwater ponds might contain a 2:1 ratio of N:P. A 20-20-0 fertilizer has roughly this N:P ratio. Fertilizers should be applied at 20 to 40 kilograms per hectare per application at two- to four-week intervals *(4)*.

Some shrimp farmers like a high proportion of diatoms in the phytoplankton community. Research has shown that a 20:1 ratio of N:P can enhance the proportion of diatoms in the phytoplankton. Nitrate seems to encourage diatoms more than ammonium, and sodium nitrate fertilizer at 10 to 20 kilograms per hectare per application can be effective in encouraging diatoms. If waters have silicate concentrations below one mg/liter as silicon (Si), applications of sodium silicate at 50 to 100 kilograms per hectare also can bolster the proportion of diatoms.

Some evidence shows that iron additions to ponds, and especially to brackishwater ponds, can stimulate phytoplankton. Chelated iron would be the best source of iron in a fertilizer, because it would be more soluble than simple iron compounds. Little is known about the benefits of trace nutrient fertilization other than iron.

Many times, fertilizers are used in combination with feeds at the beginning of production cycles. When ponds are initially filled with water, there is little plankton and benthos, and small fish or crustaceans stocked into such ponds cannot utilize the feed efficiently. Therefore, fertilizers can be used to initiate the plankton bloom and stimulate benthos to provide supplemental, natural food organisms. Turbidity by the plankton also discourages underwater weeds. Fertilization should begin one or two weeks before stocking fish or crustaceans to produce green water. After a few weeks, fertilization may be stopped because nutrients from feed will maintain the plankton bloom.

Organic Fertilizers

Animal manures can be used as fertilizers. However, these materials have several disadvantages compared to chemical fertilizers. They are of inconsistent quality, their nutrient content is low, they must be applied in large amounts, an oxygen demand results from their use, they may contain antibiotics, they often have high concentrations of heavy metals, they encourage the growth of unwanted filamentous algae, they are unpleasant to handle, and some consumers might be offended by products from a manure-based production system. In rural areas where people cannot afford chemical fertilizers, animal manures are often the only fertilizers available. However, where chemical fertilizers can be afforded, they are much superior to animal manures. Application rates for manures often are as high as 250 to 500 kilograms per hectare per week.

Pond Preparation

Organic fertilizers serve as food for zooplankton, and in some types of aquaculture, use of organic fertilizers in pond preparation is desirable to encourage the rapid development of zooplankton blooms to serve as food for young fish or crustaceans. Plant or animal meals are better organic fertilizers than animal manures. Usually, applications of 25 to 50 kilograms per hectare of plant meals–for example, soybean meal, alfalfa leaf meal, cottonseed meal, rice bran, etc., or fish meal–at four- or five-day intervals can quickly establish a zooplankton bloom. Usually, meals are applied in conjunction with chemical fertilizers.

LIMING

Liming materials are used to neutralize acidity and increase pH of acidic soils and waters. The three most common liming materials are agricultural limestone (pulverized calcium carbonate or dolomite), hydrated lime (calcium hydroxide), and quick lime (calcium oxide). The two sources of acidity in natural water are strong acids, usually sulfuric acid, and carbon dioxide. Water with pH below 4.5 contains strong acid, while at higher pH values, acidity results from carbon dioxide. Liming materials react with hydrogen ion and carbon dioxide as follows:

<u>Reaction with hydrogen ion</u>

$$CaCO_3 + 2H^+ = Ca^{2+} + H_2O + CO_2$$

$$Ca(OH)_2 + 2H^+ = Ca^{2+} + 2H_2O$$

$$CaO + 2H^+ = Ca^{2+} + H_2O$$

<u>Reaction with carbon dioxide</u>

$$CaCO_3 + CO_2 + H_2O = 2HCO_3^-$$

$$Ca(OH)_2 + 2CO_2 = Ca^{2+} + 2HCO_3^-$$

$$CaO + 2CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$$

All three liming materials have the same reaction in water. However, calcium oxide and calcium hydroxide can cause pH to increase to a level toxic to fish or other aquatic organisms. Both materials are hazardous to humans because of their caustic properties. Thus, agricultural limestone, which is neither hazardous to aquatic organisms or humans, is the best liming material for aquaculture.

Liming is beneficial in ponds with pH less than 6 or in ponds with low total alkalinity. In most types of aquaculture, a total alkalinity of 20 milligrams per liter is adequate, but in tilapia, channel catfish, or crustacean ponds, a total alkalinity of 50 milligrams per liter or more is desirable. Liming materials are not fertilizers, but they will improve the response to fertilization in acidic, low alkalinity ponds. The effects of liming on water quality are as follows:

- Increase pH of soil.
- Increase alkalinity and hardness of water.
- Flocculate suspended soil particles.
- Increase the buffering capacity of the water.
- Increase the availability of carbon for photosynthesis.
- Enhance bacterial activity in soil.
- Increase availability of phosphorus.

Acting in combination with fertilization, these improvements in water quality can lead to greater production of culture species. Of course, if ponds are not acidic, liming will not be beneficial.

Pillai and Boyd *(15)* present a fairly simple laboratory procedure for determining the lime requirement of pond soils. This procedure will work on all soils except acid-sulfate soils. Boyd *(2)* provides a lime requirement procedure for acid-sulfate soils. When the lime requirement cannot be measured, applying 1,000 kilograms per hectare of agricultural limestone is recommended. If the water is still acidic after two or three weeks, additional increments of 1,000 kilograms per hectare of agricultural limestone should be applied until the desired effect is achieved. Some authors recommend applying small amounts of liming materials (100 to 200 kilograms per hectare). Such small applications are unlikely to increase pH or alkalinity much.

When lime is applied to ponds, it should be spread uniformly over the entire bottom of an empty pond or over the entire surface of a full pond. One good application of lime usually will suffice for three to five years.

Liming is used extensively in brackishwater ponds, but most of these waters already have 60 to 120 milligrams per liter of total alkalinity. Liming materials will normally not dissolve in such waters, so adding them to the water is probably not useful. Of course, application of agricultural limestone to the bottoms of empty brackishwater ponds between crops is a good way to maintain soil pH. Usually, 1,000 kilograms per hectare of limestone is adequate for pond bottom treatments.

TOXIC METABOLITES

As a result of metabolic activity by organisms in ponds, carbon dioxide, ammonia, nitrite, and hydrogen sulfide sometimes may reach harmful concentrations.

Carbon Dioxide

High concentrations of carbon dioxide can be tolerated by aquacultural species, although fish are known to avoid carbon dioxide concentrations as low as five milligrams per liter. Most aquacultural species will survive in waters containing up to 60 milligrams per liter of carbon dioxide, provided dissolved oxygen concentrations are high. When dissolved oxygen concentrations are low, the presence of appreciable carbon dioxide hinders uptake of oxygen. Unfortunately, carbon dioxide concentrations normally are high when dissolved oxygen concentrations are low. This results because carbon dioxide is released in respiration and utilized in photosynthesis. Dissolved oxygen concentration declines when photosynthesis is not proceeding as rapidly as respiration; thus, carbon dioxide accumulates because it is not removed for use in photosynthesis.

Because of the necessity of light for photosynthesis, carbon dioxide concentrations increase at night and decrease during the day. High concentrations of carbon dioxide also occur in ponds during cloudy weather and following die-offs of phytoplankton or filamentous algae.

Removing carbon dioxide from pond waters is seldom practical. However, removing carbon dioxide from tanks or other containers in which aquatic creatures are reared or held is often necessary. Removal may be effected by applying calcium hydroxide [$Ca(OH)_2$] or calcium oxide (CaO). Theoretically, 0.84 milligrams per liter of calcium hydroxide should remove one milligram per liter carbon dioxide, and 0.64 milligrams per liter of calcium oxide should remove one milligram per liter of carbon dioxide. Because of the low solubility of calcium oxide and calcium hydroxide, 1.5 to two times the theoretical quantity should be applied to facilitate rapid removal of carbon dioxide.

Ammonia

Ammonia reaches pond water as a by-product of metabolism by creatures and by decomposition of organic matter by bacteria. In water, ammonia nitrogen occurs in two forms, un-ionized ammonia (NH_3) and ammonium ion (NH_4^+), in a pH and temperature dependent equilibrium:

$$NH_3 + H_2O = NH_4^+ + OH^-.$$

As pH rises, un-ionized ammonia increases relative to ammonium ion. Water temperature also causes an increase in the proportion of un-ionized ammonia, but the effect of temperature is less than that of pH. Analytical procedures for ammonia nitrogen measure both un-ionized and ionized ammonia. Percentages of un-ionized ammonia at different temperature and pH values are available *(2)*.

The toxicity of ammonia to fish and other aquatic creatures is attributed primarily to the un-ionized form. As ammonia concentrations in water increase, ammonia excretion by aquatic organisms diminishes, and levels of ammonia in blood and other tissue increase. The result is an elevation in blood pH and adverse effects on enzyme-catalyzed reactions and membrane stability. Ammonia increases oxygen consumption by tissues, damages gills, and reduces the ability of blood to transport oxygen. Disease susceptibility also increases in organisms exposed to sub-lethal concentrations of ammonia.

The tolerance of aquatic organisms to ammonia varies with species, physiological condition, and environmental factors. Lethal concentrations to warmwater fish and crustaceans for short-term exposure (24 to 96 hours) are between 0.4 and two milligrams per liter of un-ionized ammonia. Percentages of un-ionized ammonia at 28°C and different pH values and concentrations of total ammonia nitrogen necessary to give 0.4 milligrams per liter un-ionized ammonia under these conditions are presented in table 10. At a pH of 7 to 8, ammonia concentration up to four or five milligrams per liter would not pose a toxicity problem in ponds. However, at a pH of 8.5 to 9.5, four to five milligrams per liter of ammonia might cause a toxicity event. Ponds seldom contain more than four or six milligrams per liter of total ammonia nitrogen. Obviously, ammonia toxicity will be a greater problem at high pH than at lower pH. Ammonia concentrations in ponds are difficult to evaluate.

TABLE 10. PH VALUES, PERCENT OF UN-IONIZED AMMONIA, AND CONCENTRATIONS OF TOTAL AMMONIA NEEDED TO GIVE 0.4 MILLIGRAMS PER LITER UN-IONIZED AMMONIA

pH	Un-ionized ammonia %	Concentration of total ammonia nitrogen mg/liter
7.0	0.70	57.14
7.5	2.22	18.02
8.0	6.55	6.11
8.5	18.40	2.17
9.0	41.23	0.97
9.5	68.21	0.59
10.0	87.52	0.46

Because of the daily cycle in pH, un-ionized ammonia concentrations change continuously. Ammonia toxicity in aquatic creatures usually is expressed by reduced growth rate instead of mortality.

High ammonia concentrations are most common in ponds with high feeding rates. Excessive use of urea or ammonium-based fertilizers such as ammonium sulfate also can lead to toxic concentrations of ammonia. The only feasible means of reducing ammonia concentration is water exchange. Claims about the effectiveness of zeolite and bacterial amendments for removing ammonia in pond environments appear false.

Nitrite

Nitrite may accumulate to concentrations of one to 10 milligrams per liter or more in water of aquaculture ponds under certain conditions. When nitrite is absorbed by fish, it reacts with hemoglobin to form methemoglobin. In this reaction, the iron in hemoglobin is oxidized from ferrous to ferric state. The resulting methemoglobin is not capable of combining with oxygen. For this reason, nitrite toxicity results in a reduction of the activity of hemoglobin or in a functional anemia. Thus, nitrite toxicity is called methemoglobinemia. Blood containing significant amounts of methemoglobin is brown, so the common term for nitrite poisoning is "brown blood disease." Crustaceans contain hemocyanin, a compound with copper instead of iron found in hemoglobin. Reactions of nitrite with hemocyanin are poorly understood, but nitrite can be toxic to crustaceans.

The methemoglobin concentration in channel catfish cultured in ponds varies from 5 to 90% of the total hemoglobin. A slight brown color is apparent when methemoglobin reaches 25 or 30% and a chocolate-brown color is obvious at concentrations of 50% or more.

Some species of fish are able to reduce methemoglobin back to hemoglobin through the action of methemoglobin reductase. When nitrite concentrations in the water decline or when fish are transferred to water with low nitrite concentration, they recover from nitrite toxicity. Although methemoglobin levels quickly decline, a severe anemia may develop because of a decrease in hemoglobin concentration. Complete recovery from nitrite intoxication may take two or three weeks. Nitrite exposure may predispose fish to bacterial infection.

Determination of the highest permissible nitrite concentration for pond waters is difficult, because the toxicity of nitrite is closely related to dissolved oxygen concentration and several other factors. However, pond managers should be concerned when nitrite concentrations exceed 10 milligram per liter as nitrite (about 0.3 milligram per liter as NO_2-N).

The simplest procedure for counteracting nitrite toxicity in fish is to treat water with sodium chloride or calcium chloride to reduce the molar ratio of nitrite to chloride. Recent research suggests that a nitrite:chloride ratio of 1:6 was necessary to prevent all effects of high nitrite concentration on channel catfish. Notice that nitrite is reported here on an NO_2 rather than NO_2-N basis. Most water quality kits measure NO_2-N rather than NO_2. The chloride application rate necessary to provide this ratio may be calculated as follows:

Chloride (mg/l) = 6 (mg/l of nitirite – mg/l of chloride).

Common salt (NaCl), which contains about 60% chloride, is the usual source of chloride for pond treatment. Water exchange or replacement also can be effective in reducing nitrite concentration.

Hydrogen Sulfide

Under anaerobic conditions, certain heterotrophic bacteria can use sulfate and other oxidized sulfur compounds as terminal electron acceptors in metabolism and excrete sulfide as illustrated below:

$$SO_4^{2-} + 8H^+ = S^{2-} + 4H_2O.$$

Sulfide is an ionization product of hydrogen sulfide and participates in the following equilibria:

$$H_2S = HS^- + H^+$$

$$HS^- = S^{2-} + H^+.$$

The pH regulates the distribution of total sulfide among its forms (H_2S, HS^-, and S^{2-}). Un-ionized hydrogen sulfide (H_2S) is toxic to aquatic organisms; the ionic forms have no appreciable toxicity. Analytical procedures measure total sulfide. The percentages of un-ionized hydrogen sulfide at different pH values at 28°C are presented in table 11. The percentage of hydrogen sulfide decreases as the pH increases. A water containing 0.01 milligrams per liter total sulfide would have an hydrogen sulfide concentration of 0.009 milligrams per liter at pH 6 (0.01 x 0.903 = 0.009); the same total sulfide concentration at pH 8.5 would contain only 0.0003 milligrams per liter hydrogen sulfide (0.01 x 0.029 = 0.0003). The percentages of un-ionized sulfide at pH 6 and pH 8.5 are 90.3% and 2.9%, respectively. These percentages are the sources of the multipliers used in the example above to convert total sulfide to un-ionized sulfide.

Table 11. Occurrence of Un-ionized Hydrogen Sulfide at Different pH Values[1]

pH	Hydrogen sulfide %
5.0	98.9
5.5	96.7
6.0	90.3
6.5	74.6
7.0	48.2
7.5	22.7
8.0	8.5
8.5	2.9
9.0	0.9

[1] Temperature is 28°C.

Concentrations of 0.01 to 0.05 milligrams per liter of hydrogen sulfide may be lethal to aquatic organisms. Any detectable concentration of hydrogen sulfide is considered undesirable. The presence of hydrogen sulfide may be recognized without water analysis, for the "rotten-egg" smell of hydrogen sulfide is detectable at very low concentration.

If water contains hydrogen sulfide, water exchange will reduce its concentration. Application of lime to raise the pH of the water will reduce the proportion of the total sulfide that is comprised of hydrogen sulfide.

MECHANICAL AERATION

Aerators are mechanical devices that increase the rate at which oxygen enters water. There are two basic techniques for aerating pond water: (1) water is splashed into the air or (2) bubbles of air are released into the water. Hence, we have "splasher" and "bubbler" aerators.

Types of splasher aerators include vertical pump, pump-sprayer, and paddle wheel aerators. A vertical pump aerator consists of a motor with an impeller (propeller) attached to its shaft. The motor is suspended below a float with a center opening and the impeller jets water into the air (figure 17). A pump-sprayer aerator employs a centrifugal pump to spray water at high velocity through holes in a manifold and into the air. This type of aerator is not used widely.

A paddle wheel aerator splashes water into the air as the paddle wheel rotates (figure 18). The small, electric paddle wheel aerator in figure 18 is the "Taiwan-style" aerator often used in Asian aquaculture. Much larger and more efficient electric paddle wheel aerators are used in channel catfish farming in the United States (figure 19). Tractor-powered, paddle wheel aerators (figure 20) can be used to supplement smaller aerators during a low dissolved oxygen crises or in ponds without electrical services. Paddle wheel aerators are probably used more widely in pond aquaculture than all other types of aerators combined.

Bubbler aerators include diffused-air systems and propeller-aspirator pumps. In a diffused-air system an air blower is employed to deliver air through an air line, and the air is released through air diffusers located on the pond bottom or suspended in the water (figure 21). The propeller-aspirator-pump aerator has a high velocity, uncased impeller at the end of a hollow shaft and housing (figure 22). In oper-

Figure 17. Vertical pump aerator.

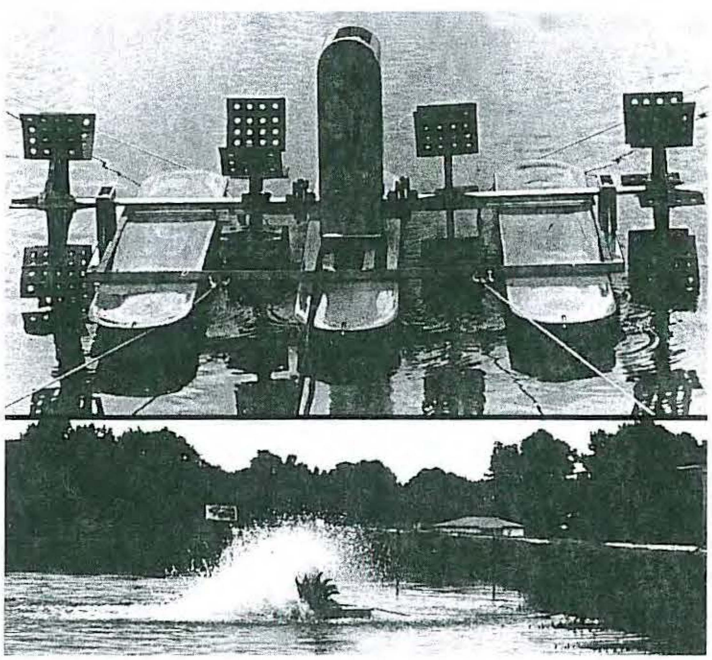

Figure 18. "Taiwan-style," electric paddle wheel aerator.

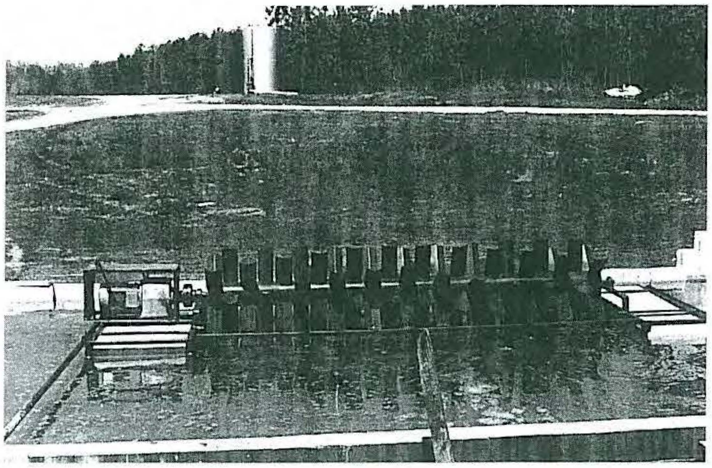

Figure 19. *Paddle wheel aerator of the type used in channel catfish farming in the United States.*

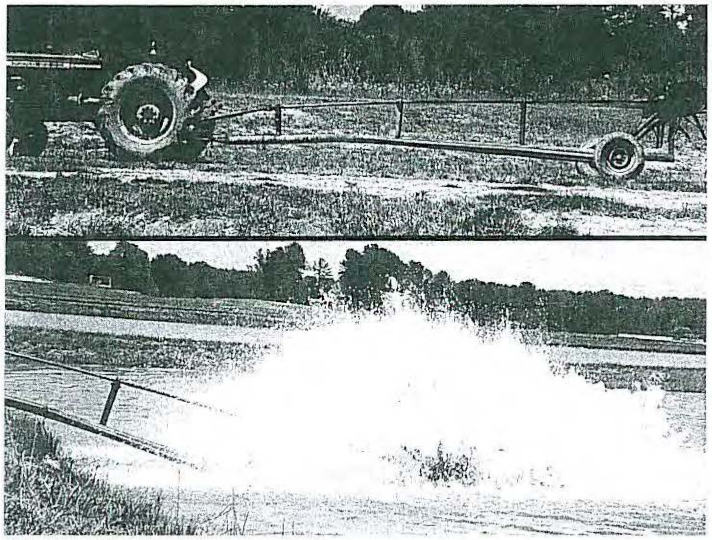

Figure 20. *Tractor-powered paddle wheel aerator.*

ation, air flows down the shaft by the venturi principle and is released into the water in fine bubbles.

Boyd and Ahmad *(5)* evaluated more than 30 aerators for aquaculture. The oxygen transfer efficiencies of aerators in kilograms of oxygen transferred per kilowatt·hour of power applied to aerator shafts for the basic types of aerators is summarized in table 12.

TABLE 12. OXYGEN TRANSFER EFFICIENCIES OF BASIC TYPES OF AERATORS

Type of aerator	Average oxygen transfer efficiency ($kg\ O_2/kw{\cdot}hr$)
Paddle wheel	2.13
Propeller-aspirator pumps	1.58
Vertical pumps	1.28
Pump sprayers	1.28
Diffused air systems	0.97

Probably the most common use of aeration is to prevent stress and mortality in aquatic creatures when occasional oxygen depletions occur. This type of aeration is commonly called emergency aeration and is a proven management tool. Fish farmers monitor dissolved oxygen concentrations and pond conditions. When they expect the dissolved oxygen concentration to fall below two or three milligrams per liter, aeration is initiated and continued until there is no longer danger of a dissolved oxygen depletion. Emergency aeration is seldom necessary on more than a few nights per year, and then it normally is needed only between midnight and dawn, during prolonged periods of cloudy weather, or after plankton die-offs.

Aeration may be applied on a continuous basis to increase production. Up to 25,000 to 30,000 kilograms per hectare per year of fish and 10,000 to 12,000 kilograms per hectare of shrimp have been produced with heavy aeration. In order to have such high production, considerable water (10 to 30% of pond volume per day) must be flushed through ponds to remove ammonia and other toxic metabolites.

A better way to use aeration is to stock ponds at a modest rate and aerate every night from midnight until dawn to assure that dissolved oxygen concentrations always are optimum. For example, in an experiment conducted at Auburn University *(12)*, channel catfish ponds were stocked at 10,000 fingerlings per hectare and fed to a maximum daily rate of 53.2 kilograms per hectare. Three ponds were aerated six hours per night from 30 May to 12 October at a modest

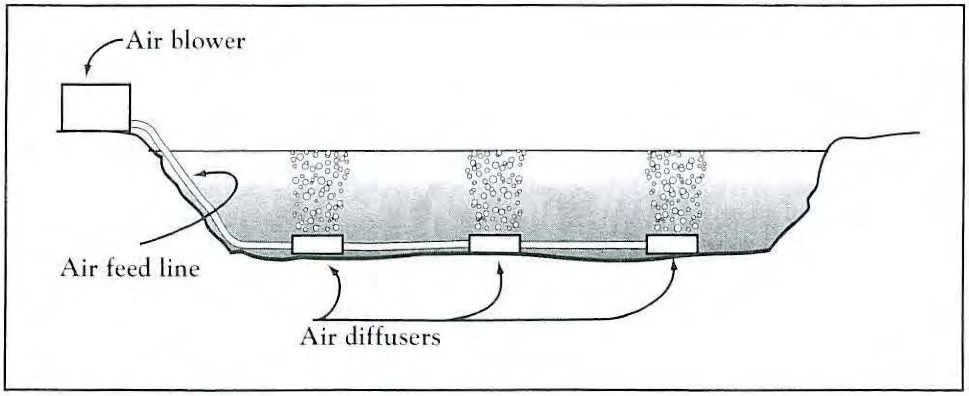

Figure 21. *Diffused-air aeration system.*

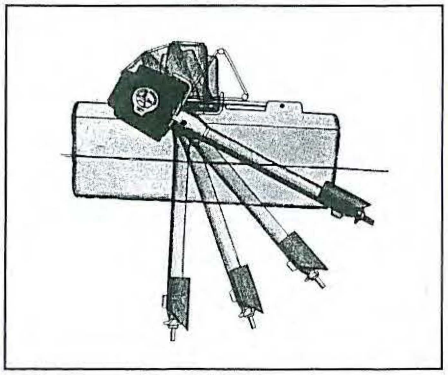

Figure 22. *Propeller-aspirator-pump aerator.*

rate. Three ponds served as un-aerated controls, but emergency aeration was occasionally applied in these ponds. Dissolved oxygen concentrations were always above four milligrams per liter in aerated ponds, but dissolved oxygen concentrations below two milligrams per liter often were recorded in un-aerated ponds. Harvest weight of fish averaged 4,810 kilograms per hectare in aerated ponds and 3,660 kilograms per hectare in un-aerated ponds. The same quantity of feed was applied to all ponds. Feed conversion values were 1.32 and 1.75 in aerated and un-aerated ponds, respectively. Production data were expanded to larger ponds for a budget analysis. Net returns to land, management, and equity capital were almost twice as great for aerated ponds as for un-aerated ponds.

The experiment was repeated in 1987 with similar results. Production in aerated ponds was 4,475 kilograms per hectare as compared to 3,551 kilograms per hectare in control ponds. Feed conversion values were 1.58 and 2.04 in aerated and un-aerated ponds, respectively. These findings suggest that nightly aeration of ponds stocked and fed at moderate rates may be more profitable than aeration of heavily stocked and fed ponds.

WATER CIRCULATION

Aquaculturists agree that water circulation in ponds is beneficial. Water circulation prevents thermal and chemical stratification. Water circulation makes the entire pond volume habitable by fish and crustaceans and minimizes the problem of dissolved oxygen depletion at the mud-water interface. Aeration of pond water causes water circulation, and propeller-aspirator-pump aerators and paddle wheel aerators are more efficient than other types in circulating pond water. However, there are devices for circulating pond water and blending surface and bottom waters that are less expensive to purchase and operate than conventional aerators.

An air-lift pump (figure 23) is a good water circulator (14). The pump is constructed of a length of PVC pipe and a PVC elbow. Air from an air blower is released through a 90° hose adaptor into the PVC pipe. If desired, an air diffuser that releases smaller bubbles of air can be placed in the pipe. The rising air bubbles lift water through the pipe and discharge it at the pond surface. A pump holder is attached between the anchor post and the pump. This holder contains a flotation device and it permits the pump to pivot. Ballast must be provided at the bottom of the pump. Water circulation requires too many air-lift pumps to induce water circulation in large ponds, so large, horizontal, axial-flow pumps have been suggested for circulating pond water. These pumps consist of a large impeller mounted in a casing about 1.5 meters in length and one meter in diameter. The impeller is turned at no more than 100 revolutions per minute and a large volume of water can be directed parallel to the pond bottom at low velocity *(11)*.

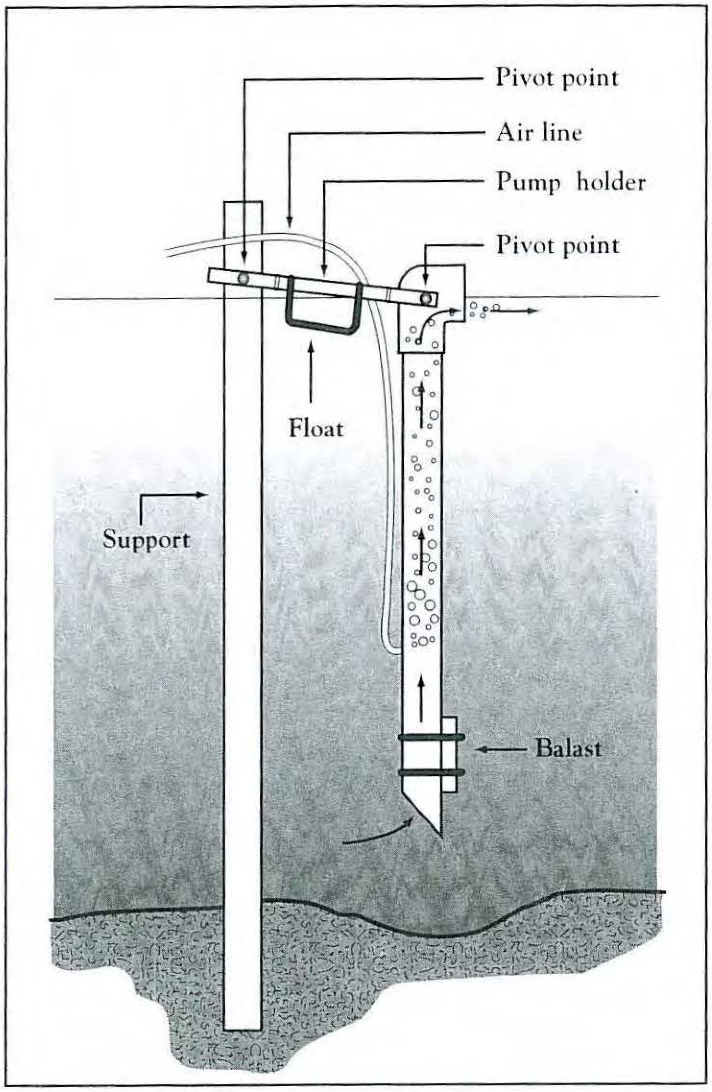

Figure 23. Air-lift pump.

MISCELLANEOUS TREATMENTS

In addition to the more common pond treatments for improving water quality that have been discussed above, many other methods are used. Some of these procedures are effective under certain conditions, while others probably have little value. A few of these treatments will be discussed.

Probiotics

Live bacterial inocula and enzyme preparations are marketed by many vendors for enhancing water quality, reducing the incidence of disease, and improving production in ponds. The idea is that pond ecosystems are deficient in certain bacteria and adding specific species or strains of bacteria will enhance the microbial community and improve conditions for production. In spite of the large number of claims and testimonials about these products and a few published reports showing small benefits, it is not known when and how to use probiotics in aquaculture. No proven way is known for determining in advance if application of probiotics will be helpful in a given pond. Pond managers should be skeptical about the claims made by vendors of probiotics.

Potassium Permanganate

This compound can be useful at concentrations of about two milligrams per liter for treating certain bacterial diseases of fish and crustaceans. The organic substances in pond water react quickly to deactivate the permanganate ion. To achieve an effective concentration of two milligrams per liter may require that two or more times as much potassium permanganate be applied to the water. The lowest concentration of potassium permanganate necessary to impart a faint purple color to the water that will persist for 15 or 20 minutes can be taken as the potassium permanganate demand. This potassium permanganate demand plus two milligrams per liter should be used as the treatment rate. Excessive concentrations of potassium permanganate can cause toxicity.

There are claims that potassium permanganate will increase dissolved oxygen concentrations and cause other improvements in water quality. Research has not provided proof of these claims.

Flocculents

Turbidity from suspended clay particles can persist in some ponds even after the source of turbidity has been eliminated. Flocculents can be used to clear the water of these particles. The most common flocculents are aluminum sulfate (alum) and calcium sulfate (gypsum). Alum is normally effective at concentrations of 25 to 40 milligrams per liter. Alum forms sulfuric acid in water and can cause the pH to drop below 5 if used in concentrations that are more than twice the total alkalinity concentration. Alum should be used with extreme caution if the application rate is as great as the total alkalinity concentration. Gypsum must be applied at 200 to 400 milligrams per liter to effect turbidity removal. Exact dose rates for alum or gypsum can be determined from dose-response trials in beakers of water. To apply, gypsum should be broadcast uniformly over pond surfaces. Alum should be dissolved in water and sprayed over pond surfaces. Care must be exercised with alum because its solutions are extremely acidic.

Sometimes, turbidity removal can be effected by applying agricultural limestone over pond surfaces at 1,000 to 2,000 kilograms per hectare. This treatment is useful where waters are of low alkalinity and need liming, because even if the treatment does not remove the turbidity, it will have beneficial effects on pH and alkalinity. Manure and hay also have been used to remove turbidity, but applications of 2,000 to 4,000 kilograms per hectare often are required.

Disinfection

Waters can be treated with toxins to kill pathogens and wild organisms before ponds are stocked. The toxin must be one that quickly degrades and does not leave toxic residues. The most popular treatments are calcium oxide (burnt lime), calcium hydroxide (hydrated lime), and calcium hypochlorite (HTH). It usually is necessary to apply about 1,000 to 2,000 kilograms per hectare of lime or 30 milligrams per liter of HTH. These substances will degrade within one or two weeks and the culture species can be stocked. In tropical nations, teaseed cake and other seed cakes have been used for eradicating wild fish from ponds before stocking. In the United States, rotenone is a popular substance for killing unwanted fish in ponds. Rotenone normally is used at about 0.05 to 0.1 milligram per liter of active ingredient.

Chlorination of pond waters with small doses of calcium or sodium hypochlorite (0.1 to 0.2 milligrams per liter) has been recommended as a way of killing bacteria, thinning phytoplankton blooms, and generally improving water quality. Experiments have failed to demonstrate any positive benefits of chlorination, and excessive doses of chlorine to pond water could harm or kill the culture species.

Lime (calcium oxide or calcium hydroxide) at 1,000 to 2,000 kilograms per hectare may be spread over pond bottoms to raise the pH and destroy pathogens. This treatment works best if a five to 10 centimeter layer of water is added to the pond after liming.

Pond Bottom Treatments

When ponds are drained between crops, bottoms can be dried to improve contact with the air and enhance oxidation of organic matter and other reduced substances by chemical and microbial processes. Drying the soil removes water from the pore spaces within the soil so that air can enter. The soil also cracks, providing additional space for air to enter. Air contains much more oxygen than water, so conditions for oxidation and decomposition are much better in a dry soil than in a wet one. Application of 1,000 to 2,000 kilograms per hectare of agricultural limestone also stimulates organic matter decomposition by bacteria if pond soil pH is below 7. Tilling of soil also can enhance decomposition through improving aeration and enhancing the oxygen supply for bacteria.

AQUATIC PLANT CONTROL

As mentioned earlier, one effective technique of controlling many species of macrophytes is through fertilization to produce plankton turbidity and shade the pond bottom. This technique is especially powerful if ponds are constructed so that no areas are shallower than about 60 centimeters. Grass carp (white amur) eat tremendous quantities of aquatic vegetation and provide a biological method for controlling macrophytes. When stocked at 60 to 80 per hectare, grass carp will control most species of macrophytes that cannot be controlled by plankton turbidity. Grass carp are even effective in controlling macrophytes in ponds that are not turbid with plankton. In small ponds, macrophytes may be controlled by cutting or by dragging them out with a rake or seine.

Herbicides are also used in fish culture to control macrophytes. The manufacturer's label gives the rate and method of application for a herbicide. The label provides information on safety precautions. Usually, the concentrations of aquatic herbicides used to kill macrophytes are safe to fish and other aquatic creatures. Decay of macrophytes killed by herbicides can cause a dissolved oxygen depletion. If ponds have extensive areas of macrophytes, one-fourth to one-fifth of the pond area should be treated at one- to two-week intervals to reduce the chance of dissolved oxygen depletion. The major limitation of herbicides for controlling macrophytes is that once the concentration of a herbicide declines to a non-toxic level, macrophytes will regrow. Thus, repeated applications of herbicides are required to control macrophytes, often at considerable expense.

Algicides are sometimes used to control phytoplankton in ponds. Copper sulfate, the most widely used algicide, will kill most species of phytoplankton at concentrations of 0.1 to 0.5 milligram per liter in waters with a total alkalinity below 40 or 50 milligrams per liter. In waters with a higher alkalinity, copper sulfate concentrations of 1.0 milligram per liter or more may be required to kill phytoplankton. A common procedure for determining the copper sulfate dose is to apply it at 0.01 times the total alkalinity concentration. Copper sulfate may be applied by dissolving it in water and distributing it over the pond surface. Alternatively, copper sulfate crystals may be placed in a burlap bag and the bag towed behind a boat until the copper sulfate dissolves. Burlap bags of copper sulfate may be positioned in ponds so that the chemical gradually dissolves and mixes with the water. Copper sulfate may also be used to treat scums of phytoplankton which drift to the leeward sides of ponds.

Phytoplankton killed by copper sulfate decompose rapidly and may result in low dissolved oxygen concentrations. Copper sulfate has no appreciable residual toxicity and phytoplankton growth will resume soon after treatment. Fish and other culture species are susceptible to copper sulfate, and in waters with an alkalinity less than 20 milligrams per liter, treatment with 0.5 to 1.0 milligrams per liter of copper sulfate may result in mortality of culture creatures.

Synthetic algicides, such as Diuron (3-(3, 4 dichlorophenyl)-1, 1-dimethyl urea) and simazine (2-chloro-4, 6-bis (ethylamino)-triazine), are sometimes used to kill phytoplankton. These algicides are extremely toxic to algae, have a long residual action, and are not toxic to fish at concentrations used to kill phytoplankton. As with copper sulfate, extensive mortality of phytoplankton following applications of synthetic algicides may result in depletion of dissolved oxygen. Some aquaculturists have attempted to "thin" phytoplankton blooms by small, periodic applications of synthetic algicides to ponds receiving heavy applications of feed. However, this practice results in prolonged periods of low dissolved oxygen concentrations and reduced yields. Also the two previously mentioned synthetic algicides are not currently labeled for algicide use in foodfish ponds in the United States.

HEAVY METALS

Fairly high concentrations of heavy metals have been reported in polluted waters in many nations. Thus, there is interest in the toxicity of heavy metals to fish and other aquacultural species. The toxicity of heavy metals to a variety of species of freshwater and marine creatures, mostly

Table 13. Toxicity of Heavy Metals of Freshwater and Marine Creatures[1]

Metal	Range of 96-hr LC50 (µg/l)	Safe level recommended by U.S.Environmental Protection Agency (µg/l)
Cadmium	80-420	10
Chromium	2,000-20,000	100
Copper	300-1,000	25
Lead	1,000-40,000	100
Mercury	10-40	0.10
Zinc	1,000-10,000	100

[1] Information obtained from various publications.

fish, were obtained from various publications and are presented in table 13. The safe levels recommended by the U.S. Environmental Protection Agency are conservative estimates, which are 10 to 100 times lower than the lowest concentrations which have been reported to harm organisms in laboratory toxicity tests.

The usual procedure for heavy metal analysis (atomic absorption spectrophotometry) measures the total concentration of a particular metal. Waters in ponds contain suspended clay particles and organic matter. Heavy metals are adsorbed onto clay particles and chelated by organic matter. Some of the heavy metals also form complexes with oxides, hydroxides, and carbonates in water. The toxicity of heavy metals is related primarily to the dissolved, ionic form of the metal, for example, Cu^{2+} or Zn^{2+}, rather than to adsorbed, chelated or complexed forms. Hence, only a small percentage of the heavy metals in most waters is in ionic form.

PESTICIDES

A number of pesticides are used on agricultural crops and pesticides can enter ponds and streams in runoff and aerial drift. Chlorinated hydrocarbon insecticides have the greatest potential for harming fish, but many organochlorine, carbamate, and other chemical compounds used for pest control are toxic to aquatic organisms. There are so many pesticides that it is not feasible to make a list of toxicities for individual compounds, but some of the most toxic compounds have 96-hour LC50 concentrations of 0.25 milligram per liter or less. The recommended safe level for a pesticide in water is usually 20 to 100 times less than the 96-hour LC50.

Apparently, the use of pesticides with long residual lives is declining in most nations, and many pesticides that are used today degrade to non-toxic forms within a few days. However, pesticides are potentially harmful until they are degraded. Aquaculture projects should be located in places that are not likely to be contaminated with pesticides. Pesticides sprayed onto fields may drift over considerable areas and reach ponds or water supply canals. Key factors for protecting ponds from pesticides are as follow: put ponds a considerable distance from pesticide-treated fields; plant trees or other high-growing vegetative cover between ponds and pesticide-treated fields to intercept airborne drift of pesticides; construct topographic barriers (ditches or terraces) to prevent runoff from fields from entering ponds; and use proper methods to apply pesticides to fields. The disposal of pesticides and pesticide containers should be done in such a way that pesticides do not contaminate waterways.

CALCULATIONS FOR TREATMENTS

Concentrations for chemical treatments of ponds are given in milligrams per liter so aquaculturists must calculate how much of a chemical to add to a pond to give the desired concentration. To calculate the amount of a chemical needed, the volume of the pond must be known. Assuming the surface area of a pond is known, the simplest technique for obtaining the average depth is to travel over the pond surface in a boat making a large S-shaped pattern and taking 20 to 30 soundings with a calibrated rod or sounding line. The average of all soundings is taken as the average depth.

Once the volume of a pond is known, it is a simple matter to calculate treatment rates. For calculations of pond treatments, one must realize that one gram per cubic meter is equivalent to one milligram per liter. The following examples illustrate how to calculate amounts of chemicals to add to ponds.

Example. A pond has a surface area of 0.26 hectare and an average depth of 1.15 meters. How much filter alum (100% pure) must be applied to the pond to give an alum concentration of 25 milligrams per liter?

(1) Since 0.26 hectare = 2,600 square meters, the pond volume is:

$$2{,}600 \text{ m}^2 \times 1.15 \text{ m} = 2{,}990 \text{ m}^3.$$

(2) Each cubic meter will require 25 grams of alum for a concentration of 25 milligrams per liter, so the amount of alum needed for the entire pond is:

$$2{,}990 \text{ m}^3 \times 25 \text{ grams/m}^3 = 74{,}750 \text{ grams.}$$

(3) A treatment of 74,750 grams equals 74.75 kilograms.

Example. The average depth of a pond is 0.57 meter and the surface area is 0.01 hectare. How much agricultural gypsum (80% pure) must be applied to produce a gypsum concentration of 50 milligrams per liter?

(1) Since 0.01 hectare = 100 square meters, the pond volume is:

$$100\ m^2 \times 0.57\ m = 57\ m^3.$$

(2) Each cubic meter will require 50 grams of gypsum for a concentration of 50 milligrams per liter, but the agricultural gypsum is only 80% pure. Therefore, we may calculate the concentration of gypsum as follows:

$$50\ \text{grams} \div 0.80 = 62.5\ \text{grams}.$$

The amount of agricultural gypsum needed for the entire pond will be:

$$57\ m^3 \times 62.5\ \text{grams}/m^3 = 3{,}562\ \text{grams or } 3.56\ \text{kg}.$$

Example. A pond with a volume of 1,000 cubic meters must be treated with a herbicide. The herbicide is a liquid with 75% active ingredient and a density of 1.05 grams per milliliter (1.05 kilograms per liter). How much of the liquid herbicide must be applied to the pond to give a concentration of one milligram per liter of active ingredient?

(1) The amount of the active ingredient to give a concentration of one milligram per liter is:

$$1{,}000\ m^3 \times 1\ \text{gram} = 1{,}000\ \text{grams} = 1.0\ \text{kg}.$$

(2) The herbicide has an active ingredient content of 75%, so the weight of herbicide containing 10 kilograms active ingredient is:

$$1.0\ \text{kg} \div 0.75 = 1.33\ \text{kg}.$$

(3) The density of the herbicide is 1.05 kilograms per liter, so the volume of the herbicide weighing 1.33 kilograms is:

$$1.33\ \text{kg} \div 1.05\ \text{kg/liter} = 1.27\ \text{liters}.$$

Thus, 1.27 liters of the liquid herbicide would give a concentration of one milligram per liter of the active ingredient when applied to the pond.

Chemicals which are applied to ponds come in a variety of formulations, including crystals, solutions, wettable powders, emulsifiable concentrates, and granules. Research stations and large aquaculture farms can afford rather elaborate equipment for applying chemicals. For example, chemicals may be dissolved in a tank of water or some other solvent and sprayed over the surface with a power sprayer. Liquids may be dispersed uniformly from a boat-mounted tank through a boom consisting of a pipe with a series of small diameter holes in its underside. A valve regulates the rate at which the solution is fed by gravity into the water, or a pump may be used to effect more uniform and forceful release. Dispensers for granules or powders may consist of hoppers with adjustable dispensing holes in the bottom. An auger is employed to prevent clogging of holes. Finally, chemicals may be released into the wash of an outboard motor propeller to effect mixing as the boat moves over the pond surface.

When the owner of one or several ponds must apply chemicals, it is usually not practical to purchase or construct an elaborate dispenser. The chemical can be dissolved or mixed in a large container of water and applied to the pond surface. The chemical may be applied with a pressurized garden sprayer, or the solution or mixture may be splashed with a dipper over the pond surface. The chemical should be dispensed as uniformly as possible. Granules may be broadcast by hand or with a small "cyclone" seeder. Crystals may be placed in a burlap bag and the bag towed behind a boat until they have dissolved. Only a little ingenuity is needed to develop a method for applying a chemical to a pond once the treatment rate has been established.

WATER ANALYSIS

Water analysis is a highly specialized field and methods for measuring the concentration of almost any possible constituent of water are available. These methods may be found in several standard water analysis manuals. The most widely used of these manuals is the "Standard Methods for the Examination of Water and Wastewater" *(10)*. To make water analyses according to standard procedures, a water analysis laboratory and a well-trained analyst are essential. In practical aquaculture, only a few water quality data are needed in making water quality management decisions. These normally include pH, total alkalinity, total hardness, dissolved oxygen, carbon dioxide, and plankton abundance. Water analysis kits that test these variables are available at a modest cost. The kits provide sufficiently accurate data on which to base management decisions. A Secchi disk, which may be constructed from common items or purchased for a small cost, may be used to estimate plankton abundance.

Sampling Water

Water samples for dissolved oxygen or carbon dioxide analyses must be collected so that they do not come in contact with the atmosphere. If a sample is supersaturated with dissolved gases, the gases are lost to the atmosphere. A number of samplers are available for collecting water for dissolved gas analyses, but the least expensive types may be obtained from the manufacturers of water analysis kits. Samples for total alkalinity, total hardness, or pH may come in contact with the air without introduction of appreciable errors in measurement. Samples of surface water may be secured by simply immersing an open-mouthed bottle and allowing it to fill. Samplers may also be constructed for obtaining water from greater depths. For example, a stoppered bottle may be attached to a wooden stick and lowered to the desired depth. The stopper may then be jerked out with an attached cord so that the bottle may fill. Once the water sample has been collected, it should be analyzed as soon as possible to prevent changes in concentrations of the constituents of interest.

Water Analysis Kits

The largest and best known manufacturer of water analysis kits is probably the Hach Company of Ames, Iowa, and Loveland, Colorado. However, kits of comparable quality may be obtained from other companies, so the use of the Hach water analysis kits in the illustrations is by no means an endorsement of Hach Company products. The directions in any water analysis kit should be followed carefully and all operations conducted with as much precision as possible. Slight errors in measuring the volumes of samples or titrating agents will be greatly magnified in the final results. For measuring total hardness or total alkalinity on samples with low concentrations (below 20 or 30 milligrams per liter) of these constituents, the volumes of samples and reagents should be increased by five times to get reliable results. Measurements of pH with water analysis kits are 0.5 to 1.0 pH units higher than the correct values obtained with a pH meter. The reagents in water analysis kits deteriorate with time and should be replaced every six to 12 months. In spite of the limitations of water analysis kits, they are often the only method available for water analysis in fish culture, and with reasonable care the kits will provide useful data. In table 14, comparisons are made between data obtained on the samples by a Hach Model AL-36B water analysis kit and by standard laboratory procedures.

More advanced, and expensive, water analysis kits are available. These kits have the capacity for measuring dissolved gases, pH, ammonia, nitrate, nitrite, phosphate, sulfate, chloride, conductivity, and several other water quality variables. The more elaborate kits are suitable for aquaculture management and for some types of research in aquaculture.

Table 14. Comparison of Determinations Made on Water Samples by Standard Methods and a Hach Water Analysis Kit (Model AL-36B)

Procedure	Sample			
	A	B	C	D
Total alkalinity (mg/liter)				
Standard method	11.0	31.8	49.6	119.7
Hach kit	15.6	33.7	49.4	116.3
Total hardness (mg/liter)				
Standard method	7.7	27.1	53.4	107.5
Hach kit	11.1	32.7	55.7	110.4
Carbon dioxide (mg/liter)				
Standard method	1.2	4.3	10.9	18.0
Hach kit	5.0	5.0	10.0	15.0
Dissolved oxygen (mg/liter)				
Standard method	1.1	2.7	4.9	8.6
Hach kit	2.0	2.8	4.0	8.0
pH				
Standard method	4.5	5.5	7.8	8.8
Hach kit	5.0	6.1	9.0	9.7

SECCHI DISK VISIBILITY

A Secchi disk is 20 centimeters in diameter, painted with black and white quadrants, and attached to a calibrated line (figure 5). The disk is weighted on the underside with a lead plate so that it will sink readily. Secchi disks may be purchased from scientific supply houses or constructed from sheet metal, plexiglass, or masonite. A flat paint should be used to prevent glare. A suitable alternative to attaching the disk to a calibrated line is to attach it from its center to a vertical meter stick. Secchi disk visibilities seldom exceed 40 or 50 centimeters in productive aquaculture systems, so measurements will seldom be limited because of the length of the meter stick.

Secchi disk visibility is not a suitable estimate of plankton unless plankton is the primary source of turbidity. An experienced observer can readily distinguish between plankton turbidity and other forms of turbidity. However, the novice must remember that plankton blooms are not always green. Plankton blooms may also impart yellow, red, brown, or black coloration to water. Usually plankton organisms are large enough that their particulate nature is obvious if water and its contents are viewed against a white background.

To obtain the Secchi disk visibility, lower the disk into the water until it just disappears and record the depth. Lower the disk a little more and then raise it until it just reappears and record the depth. In making these measurements, view the disk from directly above. The average of the two depth readings is the Secchi disk visibility. Conditions for taking Secchi disk measurements should be standardized. A good practice is to make measurements on calm days between 9 a.m. and 3 p.m. If possible, make readings when the sun is not behind clouds. Make measurements on the lee (downwind) side of the boat or pier with the sun behind you. Even when conditions are carefully standardized, Secchi disk visibilities obtained at the same time by different observers for the same body of water will vary slightly. Furthermore, the same observer may obtain slightly different readings if the disk is viewed in the same pond at different times of the day. In practice these slight variations are not critical. In the absence of a Secchi disk, any white object or even the palm of your hand can be used to judge turbidity in pond waters.

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CELSIUS TO FAHRENHEIT DEGREES

°C	°F	°C	°F	°C	°F
0	32.0	14	57.2	28	82.4
1	33.8	15	59.0	29	84.2
2	35.6	16	60.8	30	86.0
3	37.4	17	62.6	31	87.8
4	39.2	18	64.4	32	89.6
5	41.0	19	66.2	33	91.4
6	42.8	20	68.0	34	93.2
7	44.6	21	69.8	35	95.0
8	46.4	22	71.6	36	96.8
9	48.2	23	73.4	37	98.6
10	50.0	24	75.2	38	100.4
11	51.8	25	77.0	39	102.2
12	53.6	26	78.8	40	104.0
13	55.4	27	80.6		

METRIC AND ENGLISH EQUIVALENTS

Metric	English
Length	
one millimeter	0.0394 inch
one centimeter	0.3937 inch
one meter	3.281 feet
Weight	
one milligram	0.00035 ounce
one gram (1,000 milligrams)	0.0353 ounce
one kilogram (1,000 grams)	2.205 pounds
Area	
one square meter	10.76 square feet
one hectare (10,000 square meters)	2.471 acres
Volume	
one milliliter	0.0338 U.S. liquid ounce
one liter (1,000 milliliters)	1.057 U.S. liquid quarts
3.785 liters	1.00 U.S. liquid gallon
Other	
one kilogram per hectare	0.892 pound per acre
one milligram per liter	1 part per million
one milligram per kilogram	1 part per million

CHEMICAL SYMBOLS OF SELECTED ELEMENTS

Element	Symbol
Aluminum	Al
Arsenic	As
Boron	B
Carbon	C
Calcium	Ca
Chlorine	Cl
Copper	Cu
Iron	Fe
Hydrogen	H
Mercury	Hg
Potassium	K
Magnesium	Mn
Manganese	Mn
Nitrogen	N
Sodium	Na
Oxygen	O
Phosphorus	P
Sulfur	S
Silicon	Si
Zinc	Zn