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Recirculating Aquaculture Tank Production Systems

An Overview of Critical Considerations

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Traditional aquaculture production in ponds requires large quantities of water. Approximately 1 million gallons of water per acre are required to fill a pond and an equivalent volume is required to compensate for evaporation and seepage during the year. Assuming an annual pond yield of 5,000 pounds of fish per acre, approximately 100 gallons of water are required per pound of fish production. In many areas of the United States, traditional aquaculture in ponds is not possible because of limited water supplies or an absence of suitable land for pond construction.

Recirculating aquaculture production systems may offer an alternative to pond aquaculture technology. Through water treatment and reuse, recirculating systems use a fraction of the water required by ponds to produce similar yields. Because recirculating systems usually use tanks for aquaculture production, substantially less land is required.

Aquatic crop production in tanks and raceways where the environment is controlled through water treatment and recirculation has been studied for decades. Although these technologies have been costly, claims of impressive yields with year-round production in locations close to major markets and with extremely little water usage have attracted the interest of prospective aquaculturists. In recent years, a variety of production facilities that use recirculating technology have been built. Results have been mixed. While there have been some notable large-scale business failures in this sector, numerous small- to medium-scale efforts continue production.

Prospective aquaculturists and investors need to be aware of the basic technical and economic risks involved in this type of aquaculture production technology. This fact sheet and others in this series are designed to provide basic information on recirculating aquaculture technology.

Critical production considerations

All aquaculture production systems must provide a suitable environment to promote the growth of the aquatic crop. Critical environmental parameters include the concentrations of dissolved oxygen, un-ionized ammonia-nitrogen, nitrite-nitrogen, and carbon dioxide in the water of the culture system. Nitrate concentration, pH, and alkalinity levels within the system are also important. To produce fish in a cost-effective manner, aquaculture production systems must maintain good water quality during periods of rapid fish growth. To ensure such growth, fish are fed high-protein pelleted diets at rates ranging from 1.5 to 15 percent of their body weight per day depending upon their size and species (15 percent for juveniles, 1.5 percent for market size).

Feeding rate, feed composition, fish metabolic rate and the quantity of wasted feed affect tank water quality. As pelleted feeds are introduced to the fish, they are either consumed or left to decompose within the system. The by-

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products of fish metabolism include carbon dioxide, ammonia-nitrogen, and fecal solids. If uneaten feeds and metabolic by-products are left within the culture system, they will generate additional carbon dioxide and ammonia-nitrogen, reduce the oxygen content of the water, and have a direct detrimental impact on the health of the cultured product.

In aquaculture ponds, proper environmental conditions are maintained by balancing the inputs of feed with the assimilative capacity of the pond. The pond's natural biological productivity (algae, higher plants, zooplankton and bacteria) serves as a biological filter that processes the wastes. As pond production intensifies and feed rates increase, supplemental and/or emergency aeration are required. At higher rates of feeding, water must be exchanged to maintain good water quality. The carrying capacity of ponds with supplemental aeration is generally considered to be 5,000 to 7,000 pounds of fish per acre (0.005 to 0.007 pound of fish per gallon of pond water).

The carrying capacity of tank systems must be high to provide for cost-effective fish production because of the higher initial capital costs of tanks compared to earthen ponds. Because of this expense and the limited capacity of the "natural" biological filtration of a tank, the producer must rely upon the flow of water through the tanks to wash out the waste by-products. Additionally, the oxygen concentration within the tank must be maintained through continuous aeration, either with atmospheric oxygen (air) or pure gaseous oxygen.

The rate of water exchange required to maintain good water quality in tanks is best described using an example. Assume that a 5,000-gallon production tank is to be maintained at a culture density of 0.5 pound of fish per gallon of tank volume. If the 2,500 pounds of fish are fed a 32% protein feed at a rate of 1.5 percent of their body weight per day, then 37.5 pounds of feed would produce approximately 1.1 pounds of ammonia-nitrogen per day. (Approximately 3 percent of the feed becomes ammonia-nitrogen.) Additionally, if the ammonia-nitrogen concentration in the tank is to be maintained at 1.0 mg/l, then a mass balance calculation on ammonia-nitrogen indicates that the required flow rate of new water through the tank would be approximately 5,600 gallons per hour (93 gpm) to maintain the specified ammonia-nitrogen concentration. Even at this high flow rate, the system also would require aeration to supplement the oxygen added by the new water.

Recirculating systems design

Recirculating production technology is most often used in tank systems because sufficient water is not available on site to "wash" fish wastes out of production tanks in a flow-through configuration or production system that uses water only once. In most cases, a flow-through requirement of nearly 100 gallons per minute to maintain one production tank would severely limit production capacity. By recirculating tank water through a water treatment system that "removes" ammonia and other waste products, the same effect is achieved as with the flow-through configuration. The efficiency with which the treatment system "removes" ammonia from the system, the ammonia production rate, and the desired concentration of ammonia-nitrogen within the tank determine the recirculating flow rate from the tank to the treatment unit. Using the example outlined above, if a treatment system removes 50 percent of the ammonia-nitrogen in the water on a single pass, then the flow rate from the tank would need to be twice the flow required if fresh water were used to flush the tank (93 gpm/0.5 = 186 gpm).

A key to successful recirculating production systems is the use of cost-effective water treatment system components. All recirculating production systems remove waste solids, oxidize ammonia and nitrite-nitrogen, remove carbon dioxide, and aerate or oxygenate the water before returning it to the fish tank (see Fig. 1). More intensive systems or systems culturing sensitive species may require additional treatment processes such as fine solids removal, dissolved organics removal, or some form of disinfection.

Waste solids constraints

Pelleted feeds used in aquaculture production consist of protein, carbohydrates, fat, minerals and water. The portion not assimilated by the fish is excreted as a highly organic waste (fecal solids). When broken down by bacteria within the system, fecal solids and uneaten feed will consume dissolved oxygen and generate ammonia-nitrogen. For this reason, waste solids should be removed from the system as quickly as possible. Waste solids can be classified into four categories: settleable, suspended, floatable and dissolved solids. In recirculating systems, the first two are of primary concern. Dissolved organic solids can become a problem in systems with very little water exchange.

Settleable solids control: Settleable solids are generally the easiest of the four categories to deal with and should be removed from the tank and filtration components as rapidly as possible. Settleable solids are those that will generally settle out of the water within 1 hour under still conditions. Settleable solids can be removed as they accumulate on the tank bottom through proper placement of drains, or they can be kept in suspension with continuous agitation and removed with a sedimentation tank (clarifier), mechanical filter (granular or screen), or swirl separator. The sedimentation and swirl separator processes can be enhanced by adding steep incline tubes (tube

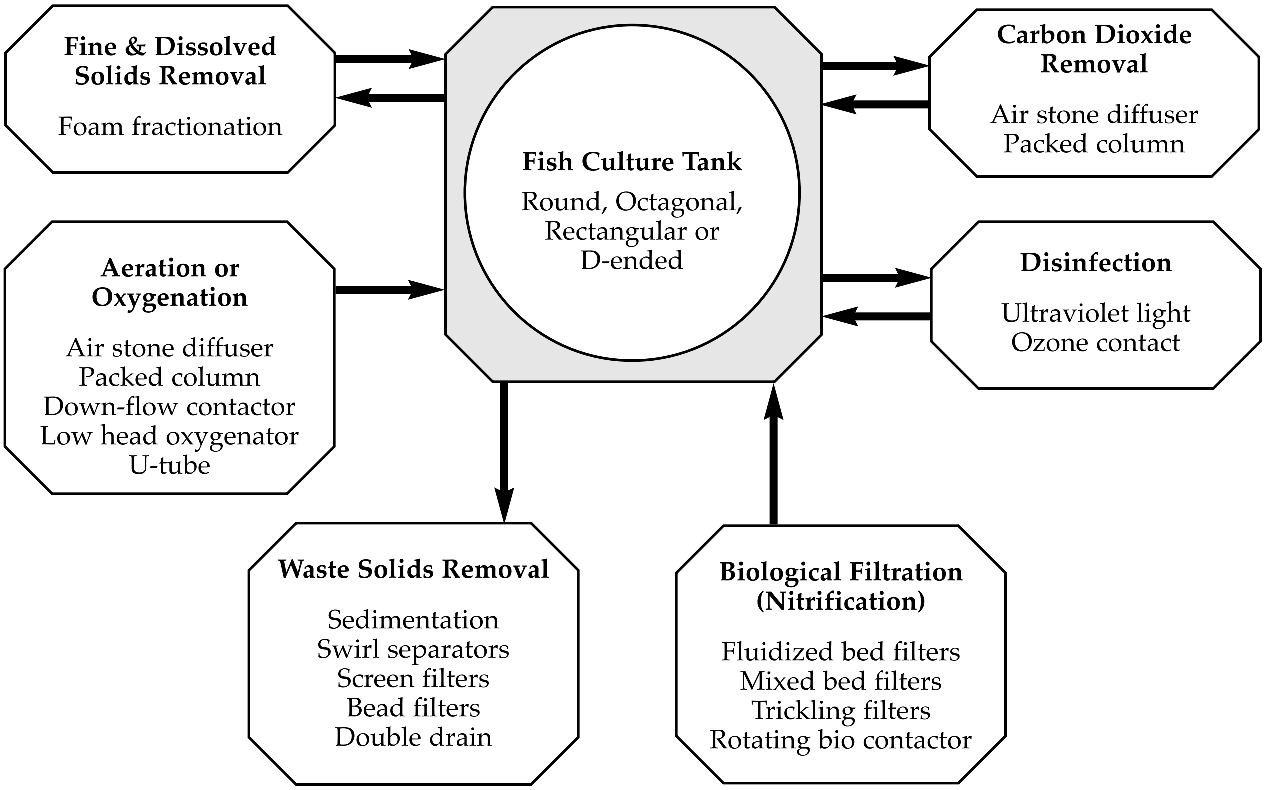

Figure 1. Required unit processes and some typical components used in recirculating aquaculture production systems.

settlers) in the sedimentation tank to reduce flow turbulence and promote uniform flow distribution.

Suspended solids control: From an aquacultural engineering point of view, the difference between suspended solids and settleable solids is a practical one. Suspended solids will not settle to the bottom of the fish culture tank and cannot be removed easily in conventional settling basins. Suspended solids are not always dealt with adequately in a recirculating production system. If not removed, suspended solids can significantly limit the amount of fish that can be grown in the system and can irritate the gills of fish. The most popular treatment method for removing suspended solids generally involves some form of mechanical filtration. The two types of mechanical filtration most commonly used are screen filtration and granular media filtration (sand or pelleted media). For more information on these devices see SRAC 453, *Recirculating Aquaculture Tank Production Systems: A Review of Component Options.*

Fine and dissolved solids control: Fine suspended solids (< 30 micrometers) have been shown to contribute more than 50 percent of the total suspended solids in a recirculating system. Fine suspended solids increase the oxygen demand of the system and cause gill irritation and damage in finfish. Dissolved organic solids (protein) can contribute significantly to the oxygen demand of the total system.

Fine and dissolved solids cannot be easily or economically removed by sedimentation or mechanical filtration technology. Foam fractionation (also referred to as protein skimming) is successful in removing these solids from recirculating tank systems. Foam fractionation, as employed in aquaculture, is a process of introducing air bubbles at the bottom of a closed column of water that creates foam at the top air/water interface. As the bubbles rise through the water column, solid particles attach to the bubbles' surfaces, forming the foam at the top of the column. The foam build-up is then channelled out of the fractionation unit to a waste collection tank. Solids concentration in the waste tank can be five times higher than that of the culture tank. Although the efficiency of foam fractionation is subject to the chemical properties of the water, the process generally can be used to significantly reduce water turbidity and oxygen demand of the culture system.

Nitrogen constraints

Total ammonia-nitrogen (TAN), consisting of un-ionized ammonia (NH_3) and ionized ammonia (NH_4^+), is a by-product of protein metabolism. TAN is excreted from the gills of fish as they assimilate feed and is produced when bacteria decompose organic waste solids within the system. The un-ionized form of ammonia-nitrogen is extremely toxic to most fish. The fraction of TAN in the un-ionized form is dependent upon the pH and temperature of the water. At a pH of 7.0, most of the TAN is in the ionized form, while at a pH of 8.75 up to 30 percent of TAN is in the un-ionized form. While the lethal concentration of ammonia-nitrogen for many species has been established, the sub-lethal effects of ammonia-nitrogen have not been well defined. Reduction in growth rates may be the most important sub-lethal effect. In general, the concentration of un-ionized ammonia-nitrogen in tanks should not exceed 0.05 mg/l.

Nitrite-nitrogen (NO_2^-) is a product of the oxidation of ammonia-nitrogen. Nitrifying bacteria (*Nitrosomonas*) in the production system utilize ammonia-nitrogen as an energy source for growth and produce nitrite-nitrogen as a by-product. These bacteria are the basis for biological filtration. The nitrifying bacteria grow on the surface of the biofilter substrate although all tank production system components will have nitrifying bacteria present to some extent. While nitrite-nitrogen is not as toxic as ammonia-nitrogen, it is harmful to aquatic species and must be controlled within the tank.

Nitrite-nitrogen binds with hemoglobin to produce methemoglobin. Methemoglobin is not capable of binding and transporting oxygen and the affected fish become starved for oxygen. The toxicity of nitrite-nitrogen is species specific. However, a common practice for reducing nitrite-nitrogen toxicity is to increase the chloride concentration of the culture water. Maintaining a chloride to nitrite-nitrogen ratio of 10:1 generally will protect against methemoglobin build-up and nitrite-nitrogen toxicity. Fortunately, *Nitrobacter* bacteria, which also are present in most biological filters, utilize nitrite-nitrogen as an energy source and produce nitrate as a by-product. In a recirculating system with a mature biofilter, nitrite-nitrogen concentrations should not exceed 10 mg/l for long periods of time and in most cases should remain below 1 mg/l.

Nitrates are not generally of great concern to the aquaculturist. Studies have shown that aquatic species can tolerate extremely high levels (> 200 mg/l) of nitrate-nitrogen in production systems. Nitrate-nitrogen concentrations do not generally reach such high levels in recirculating systems. Nitrate-nitrogen is either flushed from a system during system maintenance operations (such as settled solids removal or filter backwashing), or denitrification occurs within a treatment system component such as a settling tank. Denitrification occurs when anaerobic bacteria metabolize nitrate-nitrogen to produce nitrogen gas that is released to the atmosphere during the aeration process. For more information on the effects of water quality on fish production, see SRAC 452, *Recirculating Aquaculture Tank Production Systems: Management of Recirculating Systems.*

Ammonia and nitrite-nitrogen control: Controlling the concentration of un-ionized ammonia-nitrogen (NH_3) in the culture tank is a primary objective of recirculating treatment system design. Ammonia-nitrogen must be "removed" from the culture tank at a rate equal to the rate of production to maintain a safe concentration. While there are a number of technologies available for removing ammonia-nitrogen from water, biological filtration is the most widely used. In biological filtration (also referred to as biofiltration), there is a substrate with a large surface area where nitrifying bacteria can attach and grow. As previously noted, ammonia and nitrite-nitrogen in the recycle stream are oxidized to nitrite and nitrate-nitrogen by *Nitrosomonas* and *Nitrobacter* bacteria, respectively. Gravel, sand, plastic beads, plastic rings, plastic tubes, and plastic plates are common biofiltration substrates. The configuration of the substrate and the manner in which it comes into contact with wastewater define the water treatment characteristics of the biological filtration unit. The most common configurations for biological filters include rotating biological contactors (RBC), fixed film reactors, expandable media filters, and mixed bed reactors. For more information on biological filters and components see SRAC 453, *Recirculating Aquaculture Tank Production Systems: A Review of Component Options.*

pH and alkalinity constraints

The measure of the hydrogen ion (H^+) concentration, or pH, in water indicates the degree to which water is either acidic or basic. The pH of water affects many other water quality parameters and the rates of many biological and chemical processes. Thus, pH is considered an important parameter to be monitored and controlled in recirculating aquaculture systems. Alkalinity is a measure of the water's capacity to neutralize acidity (hydrogen ions). Bicarbonate (HCO_3^-) and carbonate (CO_3^-) are the predominant bases or sources of alkalinity in most waters. Highly alkaline waters are more strongly buffered against pH change than less alkaline waters.

Nitrification is an acid-producing process. As ammonia-nitrogen is transformed to nitrate-nitrogen by nitrifying bacteria, hydrogen ions are produced. As hydrogen ions combine with bases such as hydroxide (OH-), carbonate and bicarbonate, alkalinity is consumed and the pH decreases. Levels of pH below 4.5 are dangerous to fish; a pH below 7.0 will reduce the activity of nitrifying bacteria. If the source water for a recirculating system is low in alkalinity, then pH and alkalinity should be monitored and alkalinity must be maintained with additions of bases. Some bases commonly used include hydrated lime [$Ca(OH)_2$] quick lime (CaO), and sodium bicarbonate ($NaHCO_3$).

Dissolved gas constraints

Although ammonia-nitrogen build-up can severely limit a recirculating system's carrying capacity, maintaining adequate dissolved oxygen (DO) concentrations in the culture tank and filter system also is of critical importance. In most cases, a system's ability to add dissolved oxygen to water will become the first limiting factor in a system's fish carrying capacity. To maintain adequate DO levels in the culture tank, oxygen must be added to the tank at a rate equal to that of the rate of consumption by fish and bacteria. The consumption rate of dissolved oxygen in a recirculating system is difficult to calculate, yet an estimate is essential for proper system design. The overall rate of oxygen consumption for a system is the sum of the respiration rate of the fish, the oxygen demand of bacteria breaking down organic wastes and uneaten food (also referred to as Biochemical Oxygen Demand or BOD), and the oxygen demand of nitrifying bacteria in the filter. The amount of oxygen required by the system is largely dictated by the length of time waste solids remain within the system and the biofilter configuration. In systems with non-submerged biofilters, where solids are removed quickly, as little as 0.3 pound of oxygen can be consumed for every pound of feed added. In systems with submerged biological filters, where solids are retained within the system between backwashings of solid-removing filters, as much as 0.75 pound of oxygen will be consumed for every pound of feed added.

Carbon dioxide (CO_2) is a by-product of fish and bacterial respiration and it can accumulate within recirculating systems. Elevated carbon dioxide concentrations in the water are not highly toxic to fish when sufficient dissolved oxygen is present. However, for most species, free carbon dioxide concentrations in the culture tank should be maintained at less than 20 mg/l to maintain good growing conditions.

The build-up of dissolved nitrogen gas is rarely a problem in warm water aquaculture systems. However, caution is advised when pressurized aeration or oxygenation systems are used because atmospheric nitrogen can become supersaturated in water if air is entrained into the pressurized flow stream. Aquatic organisms subjected to elevated concentrations of dissolved nitrogen gas can develop "gas bubbles" in their circulatory systems and die.

Maintaining adequate dissolved oxygen levels and minimizing carbon dioxide concentrations in the culture tank cannot be overlooked in recirculating system design. In a typical intensively loaded recirculating system, aeration or oxygenation system failure can lead to a total loss of the fish crop in $^1/_2$ hour or less.

Aeration and Degassing: The addition of atmospheric oxygen to water or the release of excess carbon dioxide from water can be accomplished in recirculating systems through a variety of devices such as air diffusers, surface agitators, and pressurized or non-pressurized packed columns. System aeration is commonly carried out in the culture tanks, although this is not a particularly good place to add dissolved oxygen. This is because the oxygen transfer efficiency of aerators drops as the concentration of dissolved oxygen increases to near saturation levels in the tank water. Because saturated conditions are desirable in the culture tank, aeration in this location is extremely inefficient.

In recirculating systems, a better place to aerate and degas water is in the recycled flow-stream just prior to re-entry into the culture tank. At this location, in systems using submerged biological filtration, the concentration of dissolved oxygen should be at its lowest and carbon dioxide concentration will be at its highest. Packed column aerators (PCAs) are an effective and simple means of aerating water that is already in a flow-stream. In a PCA, water low in oxygen is introduced into a small tower filled with plastic medium. A perforated plate or spray nozzle evenly distributes the incoming water over the medium. The packed column is operated under non-flooded conditions so that air exchange through the tower is maintained. If the PCA is to be used for carbon dioxide stripping, a low pressure air blower will be required to provide a large quantity of air flow through the packed medium.

A number of recirculating system designs use air-lift pumps (vertical pipes with air injection) to recycle water through treatment processes and back to the culture tank. Air lifts agitate the water with air bubbles in the process and remove CO_2 and add dissolved oxygen.

Pure Oxygen Injection: In intensive production systems, the rate of oxygen consumption by the fish and bacteria may exceed the capabilities of typical aeration equipment to diffuse atmospheric oxygen into the water. In these cases, pure gaseous oxygen diffusion is used to increase the rate of oxygen addition and allow for a higher oxygen utilization rate. The saturation concentration of atmospheric oxygen in water rarely exceeds 8.75 mg/l in warm water applications ($> 20^o$ C). When pure oxygen is used with gas diffusion systems, the saturation concentration of oxygen in water is increased nearly five fold to 43 mg/l at standard atmospheric pressure. This condition allows for more rapid transfer of oxygen into water even when the ambient tank dissolved oxygen concentration is maintained close to atmospheric saturation ($>$ 7 mg/l).

A measure of success in using pure oxygen in aquaculture is the oxygen absorption efficiency of the injection or diffusion equipment. The absorption efficiency is defined as the ratio of the weight of oxygen absorbed by the water to the weight of oxygen applied through the diffusion or injection equipment. Properly designed oxygen diffusion devices can produce an oxygen absorption efficiency of more than 90 percent. However, as with tank aeration (with air), the culture tank is not the best location for oxygen diffusion with common "air stone" diffusers. Because of the short contact time of bubbles rising through a shallow (< 6 feet) water column in tanks, air stone diffusers have oxygen absorption efficiencies of not greater than 40 percent. Efficient oxygen injection systems are designed to maximize both the oxygen/water contact area and time. This can be achieved through the use of a counter-current contact column, a closed packed-column contact unit, a u-tube column or a downflow bubble contactor. For more information on aeration and oxygenation equipment see SRAC 453, *Recirculating Aquaculture Tank Production Systems: Component Options.*

Other production considerations

There have not been many well-documented successes in large-scale fish production in recirculating systems. Most reports of successful production have been from producers who supply fish live or on ice to local niche markets. These high-priced markets appear to be necessary for financial success due to the high cost of fish production in recirculating systems. In fact, the variable costs (feed, fingerling, electricity and labor) of producing fish in recirculating systems is not much different than other production methods. Where pond culture methods require a great deal of electricity (at least 1 kW per acre of pond) for aeration during the summer months, recirculating systems have a steady electrical load over the entire year. While it may appear that recirculating systems require more labor in system upkeep and maintenance than ponds, when the long hours of nightly labor for checking oxygen in ponds and moving emergency aerators and harvest effort are considered, the difference is minimal. Recirculating systems can actually have an advantage in reducing feed costs. Tank production systems generally yield better feed conversion ratios than pond systems.

Why, then, are production costs generally higher for recirculating systems? The answer usually can be found when comparing the capital cost of these systems.

Comparing the investment costs of recirculating systems with other production methods is critical in making an informed economic evaluation. Construction costs of pond production systems in the Southeast are approximately 90 cents per pound of annual production. Recirculating systems, on the other hand, cost between $1 and $4 per pound of annual production. A $1 increase in investment cost per pound of annual production can add more than 10 cents per pound to the production cost of fish.

Given these conditions, producers using recirculating technology generally do not attempt to compete in the same markets as pond producers. However, in specialty high-value niche markets, such as gourmet foods, tropical or ornamental fish, or year-round supply of fresh product, recirculating system products are finding a place. The key to niche market success is to identify the market size and meet commitments before market expansion. In most cases, niche markets will limit the size of the production units.

Before investing in recirculating systems technology, the prospective aquaculturist should visit a commercial system and learn as much about the technology as possible. As in all aquaculture enterprises, the decision to begin production and the size of the production unit one chooses should be based on the market.

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Recirculating Aquaculture Tank Production Systems

Management of Recirculating Systems

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Recirculating systems for holding and growing fish have been used by fisheries researchers for more than three decades. Attempts to advance these systems to commercial scale food fish production have increased dramatically in the last decade. The renewed interest in recirculating systems is due to their perceived advantages, including: greatly reduced land and water requirements; a high degree of environmental control allowing year-round growth at optimum rates; and the feasibility of locating in close proximity to prime markets.

Unfortunately, many commercial systems, to date, have failed because of poor design, inferior management, or flawed economics. This publication will address the problems of managing a recirculating aquaculture system so that those contemplating investment can make informed decisions. For information on theory and design of recirculating systems refer to SRAC Publication No. 451, *Recirculating Aquaculture Tank Production Systems: An Overview of Critical Considerations,* and SRAC Publication No. 453, *Recirculating Aquaculture Tank Production Systems: Component Options.*

Recirculating systems are mechanically sophisticated and biologically complex. Component failures, poor water quality, stress, diseases, and off-flavor are common problems in poorly managed recirculating systems. Management of these systems takes education, expertise and dedication.

Recirculating systems are biologically intense. Fish are usually reared intensively (0.5 pound / gallon or greater) for recirculating systems to be cost effective. As an analogy, a 20-gallon home aquarium, which is a miniature recirculating system, would have to maintain at least 10 pounds of fish to reach this same level of intensity. This should be a sobering thought to anyone contemplating the management of an intensive recirculating system.

System operation

To provide a suitable environment for intensive fish production, recirculating systems must maintain uniform flow rates (water and air / oxygen), fixed water levels, and uninterrupted operation.

The main cause of flow reduction is the constriction of pipes and air diffusers by the growth of fungi, bacteria and algae, which proliferate in response to high levels of nutrients and organic matter. This can cause increases or decreases in tank water levels, reduce aeration efficiency, and reduce biofilter efficiency. Flow rate reduction can be avoided or mitigated by using oversized pipe diameters and configuring system components to shorten piping distances. The fouling of pipes leaving tanks (by gravity flow) is easily observed because of the accompanying rise in tank water level. If flow rates gradually decline, then pipes must be cleaned. A sponge, cleaning pad or brush attached to a plumber’s snake works well for scouring pipes. Air diffusers should be cleaned periodically by soaking them in muriatic acid (available at plumbing suppliers).

Flow blockage and water level fluctuations also can result from the clogging of screens used to retain fish in the rearing tanks. Screen mesh should be the largest size that will retain the fish (usually $^{3}/_{4}$ to 1 inch). The screened area around pipes should be much larger than the pipe diameter, because a few dead fish can easily block a pipe. Screens can be made into long cylinders or boxes that attach to pipes and have a large surface area to prevent blockage. Screens should be tight-

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ly secured to the pipe so that they cannot be dislodged during feeding, cleaning and harvesting operations.

An essential component of recirculating systems is a backup power source (see SRAC Publication No. 453). Electrical power failures may not be common, but it only takes a brief power failure to cause a catastrophic fish loss. For example, if a power failure occurred in a warmwater system (84° F) at saturated oxygen concentrations containing 1/2-pound fish at a density of 1/4 pound of fish per gallon of water, it will take only 16 minutes for the oxygen concentration to decrease to 3 ppm, a stressful level for fish. The same system containing 1-pound fish at a density of 1 pound of fish per gallon would plunge to this stressful oxygen concentration in less than 6 minutes. These scenarios should give the prospective manager a sobering feeling for how important backup power is to the integrity of a recirculating system.

Certain components of backup systems need to be automatic. An automatic transfer switch should start the backup generator in case personnel are not present. Automatic phone alarm systems are inexpensive and are essential in alerting key personnel to power failures or water level fluctuations. Some phone alarm systems allow in-dialing so that managers can phone in and check on the status of the system. Other component failures can also lead to disastrous results in a very short time. Therefore, systems should be designed with essential backup components that come on automatically or can be turned on quickly with just a flip of a switch. Finally, one of the simplest backups is a tank of pure oxygen connected with a solenoid valve that opens automatically during power failures. This oxygen-solenoid system can provide sufficient dissolved oxygen to keep the fish alive during power failures.

Biological filters (biofilters) can fail because of senescence, chemical treatment (e. g., disease treatment), or anoxia. It takes weeks to months to establish or colonize a biofilter. The bacteria that colonize a biofilter grow, age and die. These bacteria are susceptible to changes in water quality (low dissolved oxygen [DO], low alkalinity, low or high pH, high CO_2, etc.), chemical treatments, and oxygen depletions. Biological filters do not take rapid change well!

Particulates

Particulate removal is one of the most complicated problems in recirculating systems. Particulates come from uneaten feed and from undigested wastes. It has been estimated that more than 60 percent of feed placed into the system ends up as particulates. Quick and efficient removal of particulates can significantly reduce the biological demand placed on the biofilter, improve biofilter efficiency, reduce the overall size of the biofilter required, and lower the oxygen demand on the system. Particulate filters should be cleaned frequently and maintained at peak efficiency. Many particulates are too small to be removed by conventional particulate filters and cause or complicate many other system problems.

Water quality management

In recirculating systems, good water quality must be maintained for maximum fish growth and for optimum effectiveness of bacteria in the biofilter (Fig. 1). Water quality factors that must be monitored and / or controlled include temperature, dissolved oxygen, carbon dioxide, pH, ammonia, nitrite and solids. Other water quality factors that should be considered are alkalinity, nitrate and chloride.

Temperature

Temperature must be maintained within the range for optimum growth of the cultured species. At optimum temperatures fish grow quickly, convert feed efficiently, and are relatively resistant to many diseases. Biofilter efficiency also is affected by temperature but is not generally a problem in warmwater systems. Temperature can be regulated with electrical immersion heaters, gas or electric heating units, heat exchangers, chillers, or heat pumps. Tempera-

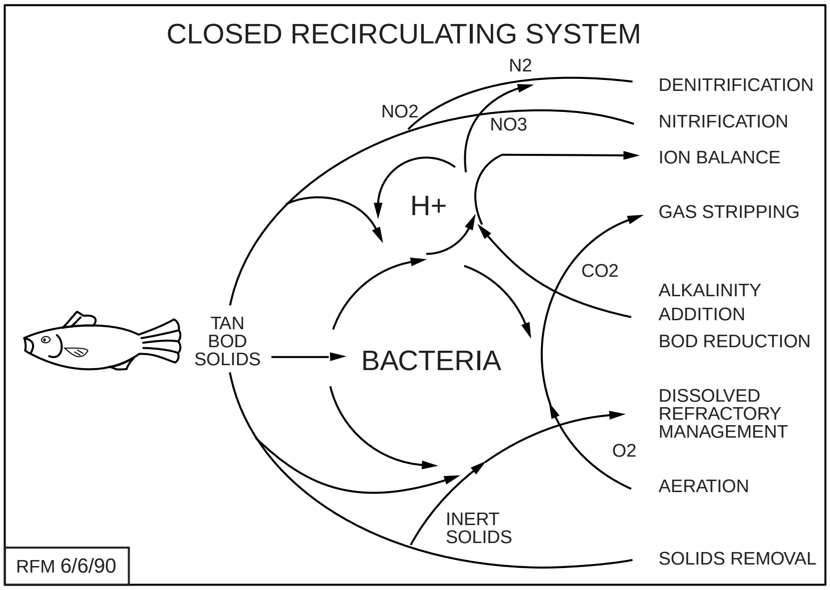


Figure 1. Diagram of fish wastes and their effects on bacterial and chemical interactions in a recirculating system.

Courtesy of Ronald F. Malone, Department of Civil Engineering, Louisiana State University, from Louisiana Aquaculture 1992, "Design of Recirculating Systems for Intensive Tilapia Culture," Douglas G. Drennan and Ronald F. Malone.

ture can be manipulated to reduce stress during handling and to control certain diseases (e.g., Ich and ESC).

Dissolved oxygen

Continuously supplying adequate amounts of dissolved oxygen to fish and the bacteria / biofilter in the recirculating system is essential to its proper operation. Dissolved oxygen (DO) concentrations should be maintained above 60 percent of saturation or above 5 ppm for optimum fish growth in most warmwater systems. It is also important to maintain DO concentrations in the biofilter for maximum ammonia and nitrite removal. Nitrifying bacteria become inefficient at DO concentrations below 2 ppm.

Aeration systems must operate continuously to support the high demand for oxygen by the fish and microorganisms in the system. As fish approach harvest size and feeding rates (pounds / system) are near their maximum levels, oxygen demand may exceed the capacity of the aeration system to maintain DO concentrations above 5 ppm. Fish show signs of oxygen stress by gathering at the surface and swimming into the current produced by the aeration device (e. g., agitator, air lift, etc.) where DO concentrations are higher. If this occurs, a supplemental aeration system should be used or the feeding rate must be reduced.

Periods of heavy feeding may be sustained by multiple or continuous feedings of the daily ration over a 15- to 20-hour period rather than in two or three discrete meals. As fish digest food, their respiration rate increases dramatically, causing a rapid decrease in DO concentrations. Feeding small amounts continuously with automatic or demand feeders allows DO to decline gradually without reaching critical levels. During periods of heavy feeding, DO should be monitored closely, particularly before and after feedings. Recirculating systems require constant monitoring to ensure they are functioning properly.

Water said to be “saturated” with oxygen contains the maximum amount of oxygen that will dissolve in it at a given temperature, salinity and pressure (Table 1). Pure oxygen systems can be incorporated into recirculating systems. These inject oxygen into a confined stream of water, creating supersaturated conditions (see SRAC Publication No. 453).

Supersaturated water, with DO concentrations several times higher than saturation, is mixed into the rearing tank water to maintain DO concentrations near saturation. The supersaturated water should be introduced into the rearing tank near the bottom and be rapidly mixed throughout the tank by currents generated from the water pumping equipment. Proper mixing of the supersaturated water into the tank is critical. Dissolved oxygen will escape into the air if the supersaturated water is agitated too vigorously. If the water is mixed too slowly, zones of supersaturation can cause gas bubble disease. In gas bubble disease, gases come out of solution inside the fish and form bubbles in the blood. These bubbles can result in death. Fry are particularly sensitive to supersaturation.

Carbon dioxide

Carbon dioxide is produced by respiration of fish and bacteria in the system. Fish begin to stress at carbon dioxide concentrations above 20 ppm because it interferes with oxygen uptake. Like oxygen stress, fish under CO_2 stress come to the surface and congregate around aeration devices (if present). Lethargic behavior and a sharply reduced appetite are common symptoms of carbon dioxide stress.

Carbon dioxide can accumulate in recirculating systems unless it is physically or chemically removed. Carbon dioxide usually is removed from the water by packed column aerators or other aeration devices (see SRAC Publication No. 453).

pH

Fish generally can tolerate a pH range from 6 to 9.5, although a rapid pH change of two units or more is harmful, especially to fry. Biofilter bacteria which are important in decomposing waste products are not efficient over a wide pH range. The optimum pH range for biofilter bacteria is 7 to 8.

The pH tends to decline in recirculating systems as bacterial nitrification produces acids and consumes alkalinity, and as carbon dioxide is generated by the fish and microorganisms. Carbon dioxide reacts with water to form carbonic acid, which drives the pH downward. Below a pH of 6, the nitrifying bacteria are inhibited and do not remove toxic nitrogen wastes.

Optimum pH range generally is maintained in recirculating systems by adding alkaline buffers. The most commonly used buffers are sodium bicarbonate and calcium carbonate, but calcium hydroxide, calcium oxide, and sodium hydroxide have been used. Calcium carbonate may dissolve too slowly to neutralize a rapid accumulation of acid.

Table 1. Oxygen saturation levels in fresh water at sea level atmospheric pressure.

Temperature		DO	Temperature		DO
ºC	ºF	mg/L (ppm)	ºC	ºF	mg/L (ppm)
10	50.0	10.92	24	75.2	8.25
12	53.6	10.43	26	78.8	7.99
14	57.2	9.98	28	82.4	7.75
16	60.8	9.56	30	86.0	7.53
18	64.4	9.18	32	89.6	7.32
20	68.0	8.84	34	93.2	7.13
22	71.6	8.53	36	96.8	6.95

Calcium hydroxide, calcium oxide and sodium hydroxide dissolve quickly but are very caustic; these compounds should not be added to the rearing tank because they may harm the fish by creating zones of very high pH. The pH of the system should be monitored daily and adjusted as necessary to maintain optimum levels. Usually, the addition of sodium bicarbonate at a rate of 17 to 20 percent of the daily feeding rate is sufficient to maintain pH and alkalinity within the desired range (Fig. 2). For example, if a tank is being fed 10 pounds of feed per day then approximately 2 pounds of bicarbonate would be added daily to adjust pH and alkalinity levels.

Alkalinity, the acid neutralizing capacity of the water, should be maintained at 50 to 100 mg as calcium carbonate/L or higher, as should hardness. Generally, the addition of alkaline buffers used to adjust pH will provide adequate alkalinity, and if the buffers also contain calcium, they add to hardness. For a more detailed discussion of alkalinity and hardness consult a water quality text.

Nitrogen wastes

Ammonia is the principal nitrogenous waste released by fish and is mainly excreted across the gills as ammonia gas. Ammonia is a byproduct from the digestion of protein. An estimated 2.2 pounds of ammonia nitrogen are produced from each 100 pounds of feed fed. Bacteria in the biofilter convert ammonia to nitrite and nitrite to nitrate, a process called nitrification. Both ammonia and nitrite are toxic to fish and are, therefore, major management problems in recirculating systems (Fig. 2).

Ammonia in water exists as two compounds: ionized (NH_4^+) and un-ionized (NH_3) ammonia. Un-ionized ammonia is extremely toxic to fish. The amount of un-ionized ammonia present depends on pH and temperature of the water (Table 2). Un-ionized ammonia nitrogen concentrations as low as 0.02-0.07 ppm have been shown to slow growth and cause tissue damage in several species of warmwater fish. However, tilapia tolerate high un-ionized ammonia concentrations and seldom display toxic effects in well-buffered recirculating systems. Ammonia should be monitored daily. If total ammonia concentrations start to increase, the biofilter may not be working properly or the feeding rate/ammonia nitrogen production is higher than the design capacity of the biofilter.

Table 2. Percentage of total ammonia in the un-ionized form at differing pH values and temperatures.

	Temperature (ºC)								
pH	16	18	20	22	24	26	28	30	32
7.0	0.30	0.34	0.40	0.46	0.52	0.60	0.70	0.81	0.95
7.2	0.47	0.54	0.63	0.72	0.82	0.95	1.10	1.27	1.50
7.4	0.74	0.86	0.99	1.14	1.30	1.50	1.73	2.00	2.36
7.6	1.17	1.35	1.56	1.79	2.05	2.35	2.72	3.13	3.69
7.8	1.84	2.12	2.45	2.80	3.21	3.68	4.24	4.88	5.72
8.0	2.88	3.32	3.83	4.37	4.99	5.71	6.55	7.52	8.77
8.2	4.49	5.16	5.94	6.76	7.68	8.75	10.00	11.41	13.22
8.4	6.93	7.94	9.09	10.30	11.65	13.20	14.98	16.96	19.46
8.6	10.56	12.03	13.68	15.40	17.28	19.42	21.83	24.45	27.68
8.8	15.76	17.82	20.08	22.38	24.88	27.64	30.68	33.90	37.76
9.0	22.87	25.57	28.47	31.37	34.42	37.71	41.23	44.84	49.02
9.2	31.97	35.25	38.69	42.01	45.41	48.96	52.65	56.30	60.38
9.4	42.68	46.32	50.00	53.45	56.86	60.33	63.79	67.12	70.72
9.6	54.14	57.77	61.31	64.54	67.63	70.67	73.63	76.39	79.29
9.8	65.17	68.43	71.53	74.25	76.81	79.25	81.57	83.68	85.85
10.0	74.78	77.46	79.92	82.05	84.00	85.82	87.52	89.05	90.58
10.2	82.45	84.48	86.32	87.87	89.27	90.56	91.75	92.80	93.84

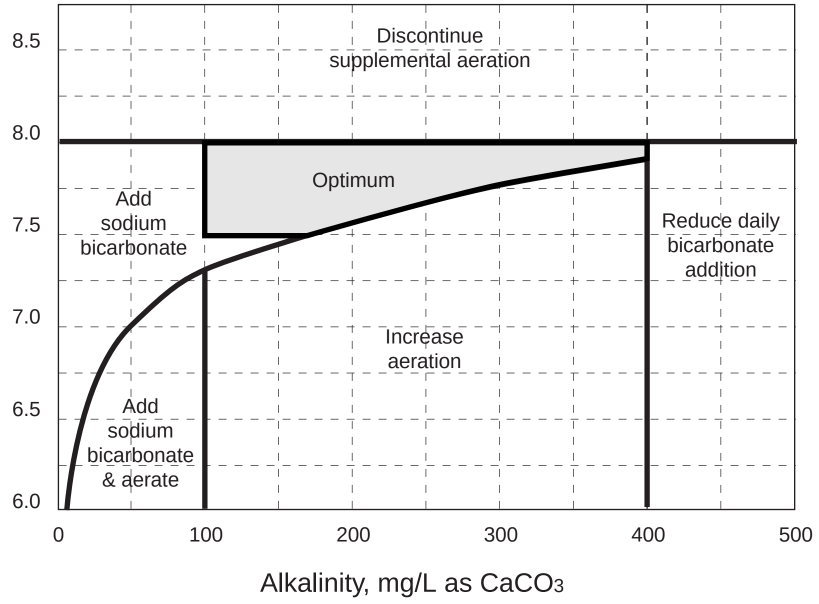


Figure 2. **The pH management diagram, a graphical solution of the ionization constant equation for carbonic acid at 25ºC.**

Courtesy of Ronald F. Malone, Department of Civil Engineering, Louisiana State University, from Master's Thesis of Peter A. Allain, 1988, "Ion Shifts and pH Management in High Density Shedding Systems for Blue Crabs (Callinectes sapidus) and Red Swamp Crawfish (Procambarus clarkii)," Louisiana State University.

Table 3. Nutrient solution for pre-activation of biofilter.

Nutrient	Concentration (ppm)
Dibasic ammonium phosphate, $(NH_4)_2HPO_4$	40
Dibasic sodium phosphate, Na_2HPO_4	40
Sea salts "solids"	40
Sea salts "liquids"	0.5
Calcium carbonate, $CaCO_3$	250

Biofilters consist of actively growing bacteria attached to some surface(s). Biofilters can fail if the bacteria die or are inhibited by natural aging, toxicity from chemicals (e. g., disease treatment), lack of oxygen, low pH, or other factors. Biofilters are designed so that aging cells slough off to create space for active new bacterial growth. However, there can be situations (e. g., cleaning too vigorously) where all the bacteria are removed. If chemical additions cause biofilter failure, the water in the system should be exchanged. The biofilter would then have to be re-activated (taking 3 or 4 weeks) and the pH adjusted to optimum levels.

During disruptions in biofilter performance, the feeding rate should be reduced considerably or feeding should be stopped. Feeding, even after a complete water exchange, can cause ammonia nitrogen or nitrite nitrogen concentrations (Fig. 3) to rise to stressful levels in a matter of hours if the biofilter is not functioning properly. Subdividing or compartmentalizing biofilters reduces the likelihood of a complete failure and gives the manager the option of "seeding" active biofilter sludge from one tank or system to another.

Activating a new biofilter (i. e., developing a healthy population of nitrifying bacteria capable of removing the ammonia and nitrite produced at normal feeding rates) requires a least 1 month. During this activation period, the normal stocking and feeding rates should be greatly reduced. Prior to stocking it is advantageous, but not absolutely necessary, to pre-activate the biofilters. Pre-activation is accomplished by seeding the filter(s) with nitrifying bacteria (available commercially) and providing a synthetic growth medium for a period of 2 weeks. The growth medium contains a source of ammonia nitrogen (10 to 20 mg/l), trace elements and a buffer (Table 3). The buffer (sodium bicarbonate) should be added to maintain a pH of 7.5. After the activation period the nutrient solution is discarded.

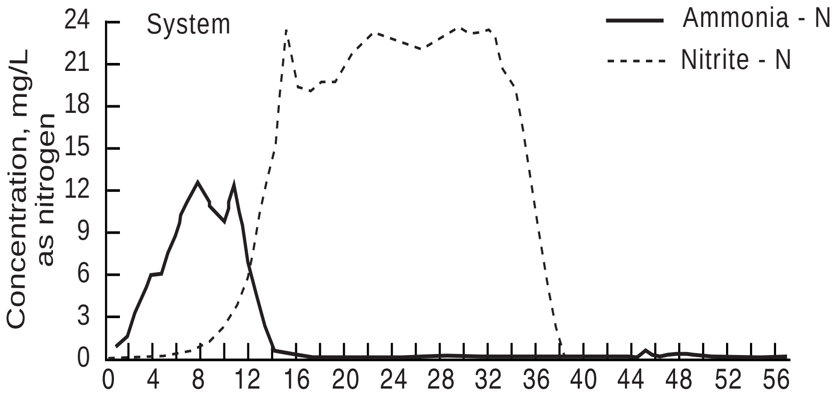


Figure 3. **Typical ammonia and nitrite curves showing time delays in establishing bacteria in biofilters.**

Courtesy of Ronald F. Malone, Department of Civil Engineering, Louisiana State University, from Master's Thesis of Don P. Manthe, 1982, "Water Quality of Submerged Biological Rock Filters for Closed Recirculating Blue Crab Shedding Systems," Louisiana State University.

Many fish can die during this period of biofilter activation. Managers have a tendency to overfeed, which leads to the generation of more ammonia than the biofilter can initially handle. At first, ammonia concentrations increase sharply and fish stop feeding and are seen swimming into the current produced by the aeration device. Deaths will soon occur unless immediate action is taken. At the first sign of high ammonia, feeding should be stopped. If pH is near 7 the fish may not show signs of stress because little of the ammonia is in the un-ionized form.

As nitrifying bacteria, known as *Nitrosomonas*, become established in the biofilter, they quickly convert the ammonia into nitrite. This conversion takes place about 2 weeks into the activation period and will proceed even if feeding has stopped. Once again, fish will seek relief near aeration and mortalities will occur soon unless steps are taken. Nitrite concentrations decline when a second group of nitrifying bacteria, known as *Nitrobacter*, become established. These problems can be avoided if time is taken to activate the biofilters slowly.

Nitrite concentrations also should be checked daily. The degree of toxicity to nitrite varies with species. Scaled species of fish are generally more tolerant of high nitrite concentrations than species such as catfish, which are very sensitive to nitrite. Nitrite nitrogen as low as 0.5 ppm is stressful to catfish, while concentrations of less than 5 ppm appear to cause little stress to tilapia. Nitrite toxicity causes a disease called "brown blood," which describes the blood color that results when normal blood hemoglobin comes in contact with nitrite and forms a compound called methemoglobin. Methemoglobin does not transport oxygen properly, and fish react as if they are under oxygen stress. Fish suffering nitrite toxicity come to the surface as in oxygen stress, sharply reduce their feeding, and are lethargic. Nitrite toxicity can be reduced or blocked by chloride ions. Usually 6 to 10 parts of chloride protect fish from 1 part nitrite nitrogen. Increasing concentrations of nitrite are a sign that the biofilter is not working properly or the biofilter is not large enough to handle the amount of waste being produced. As with ammonia buildup, check pH, alkalinity and dissolved oxygen in the biofilter. Reduce feeding and be prepared to flush the system with fresh water or add salt (NaCl) if toxic concentrations develop.

Nitrate, the end product of nitrification, is relatively nontoxic except at very high concentrations (over 300 ppm). Usually nitrate does not build up to these concentrations if some daily exchange (5 to 10 percent) with fresh water is part of the management routine. Also, in many recirculating systems some denitrification seems to occur within the system that keeps nitrate concentrations below toxic levels. Denitrification is the bacteria-mediated transformation of nitrate to nitrogen gas, which escapes into the atmosphere.

Solids

Solid waste, or particulate matter, consists mainly of feces and uneaten feed. It is extremely important to remove solids from the system as quickly as possible. If solids are allowed to remain in the system, their decomposition will consume oxygen and produce additional ammonia and other toxic gases (e. g., hydrogen sulfide). Solids are removed by filtration or settling (SRAC Publication No. 453). A considerable amount of highly malodorous sludge is produced by recirculating systems, and it must be disposed of in an environmentally sound manner (e. g., applied to agricultural land or composted).

Very small (colloidal) solids remain suspended in the water. Although the decay of this material consumes oxygen and produces some additional ammonia, it also serves as attachment sites for nitrifying bacteria. Therefore, a low level of suspended solids may serve a beneficial role within the system as long as they do not irritate the fishes' gills.

If organic solids build up to high levels in the system, they will stimulate the growth of microorganisms that produce off-flavor compounds. The concentration of solids at which off-flavor compounds develop is not known, but the system water should never be allowed to develop a foul or fecal smell. If offensive odors develop, increase the water exchange rate, reduce feeding, increase solids removal, and/or enlarge biofilters.

Chloride

Adding salt (NaCl) to the system is beneficial not only for the chloride ions, which block nitrite toxicity, but also because sodium and chloride ions relieve osmotic stress. Osmotic stress is caused by the loss of ions from the fishes' body fluids (usually through the gills). Osmotic stress accompanies handling and other forms of stress (e. g., poor water quality). A salt concentration of 0.02 to 0.2 percent will relieve osmotic stress. This concentration of salt is beneficial to most species of fish and invertebrates. It should be noted that rapidly adding salt to a recirculating system can decrease biofilter efficiency. The biofilter will slowly adjust to the addition of salt but this adjustment can take 3 to 4 weeks. Table 4 summarizes general water quality requirements of recirculating systems.

Water exchange

Most recirculating systems are designed to replace 5 to 10 percent of the system volume each day with new water. This amount of exchange prevents the build-up of nitrates and soluble organic matter that would eventually cause problems. In some situations, sufficient water may not be available for these high exchange rates. A complete water exchange should be done after each production cycle to reduce the build-up of nitrate and dissolved organics.

For emergency situations it is recommended that the system have an auxiliary water reservoir equal to one complete water exchange (flush). The reservoir should be maintained at the proper temperature and water quality.

Fish production management

Stocking

Fish management starts before the fish are introduced into the recirculating system. Fingerlings should be purchased from a reputable producer who practices genetic selection, knows how to carefully handle and transport fish, and does not have a history

Table 4. Recommended water quality requirements of recirculating systems.

Component	Recommended value or range
Temperature	optimum range for species cultured - less than 5º F as a rapid change
Dissolved oxygen	60% or more of saturation, usually 5 ppm or more for warmwater fish and greater than 2 ppm in biofilter effluent
Carbon dioxide	less than 20 ppm
pH	7.0 to 8.0
Total alkalinity	50 to 100 ppm or more as $CaCO_3$
Total hardness	50 to 100 ppm or more as $CaCO_3$
Un-ionized ammonia-N	less than 0.05 ppm
Nitrite-N	less than 0.5 ppm
Salt	0.02 to 0.2 %

of disease problems in his/her hatchery. Starting with poor quality or diseased fingerlings almost ensures failure.

Fish should be checked for parasites and diseases before being introduced into the system. New fish may need to be quarantined from fish already in the system so that diseases will not be introduced. A few fish should be checked for parasites and diseases by a certified fish diagnostician. Once diseases are introduced into a recirculating system they are generally hard to control, and treatment may disrupt the biofilter.

Fish are usually hauled in cool water. As they come into the system they usually have to be tempered or gradually acclimated to the system temperature and pH. Fish can generally take a 5º F change without much problem. Temperature changes of more than 5º F should be done at about 1º F every 20 to 30 minutes. Stress can be reduced if the system is cooled to the temperature of the hauling water and then slowly increased over a period of several hours to days.

Recirculating systems must operate near maximum production (i. e., maximum risk) capacity at all times to be economical. It is not cost effective to operate pumps and aeration devices when the system is stocked with fingerlings at only one-tenth of the system's carrying capacity. Therefore, fingerlings should be stocked at very high rates, in the range of 30 fish per cubic foot. Feeding rates should be optimum for rapid growth and near the system maximum—the highest feeding rates at which acceptable water quality conditions can be maintained. When more feed is required, fish stocks should be split and moved to new tanks. This would gradually reduce the stocking rate over the production cycle.

Another approach is to divide the rearing tank(s) into compartments with different size groups of fish in each compartment. In this approach, the optimum feeding rate for all the compartments is consistently near the biofilter's maximum performance. As one group of fish is harvested, fingerlings are immediately stocked into the vacant compartment or tank. Compartment size within a tank may be adjusted as fish grow, by using movable screens.

Feeding

Knowing how much to feed fish without overfeeding is a problem in any type of fish production. Feeding rates are usually based on fish size. Small fish consume a higher percent of their body weight per day than do larger fish (Table 5). Most fish being grown for food will be stocked as fingerlings. Fingerlings consume 3 to 4 percent of their body weight per day until they reach 1/4 to 1/2 pound, then consume 2 to 3 percent of their body weight until being harvested at 1 to 2 pounds. A rule-of-thumb for pond culture is to feed all the fish will consume in 5 to 10 minutes. Unfortunately, this method can easily lead to overfeeding. Overfeeding wastes feed, degrades water quality, and can overload the biofilter.

Table 5. Estimated food consumption by size of a typical warmwater fish.

Average weight per fish (lbs.)	Average weight per fish (g)	Body weight consumed (%)
0.02	9	5.0
0.04	18	4.0
0.06	27	3.3
0.25	113	3.0
0.50	227	2.75
0.75	340	2.5
1.0	454	2.2
1.5	681	1.8

Table 6 approximates a feeding schedule for a warmwater fish (e.g., tilapia) stocked into an 84º F recirculating system as fry and harvested at a weight of 1 pound after 250 feeding days. Feed conversion is estimated at 1.5: 1, or 1.5 pounds of feed to obtain 1 pound of gain.

Tables 5 and 6 are estimates and should be used only as guidelines which can change with differing species and temperatures.

Growth and feed conversion are estimated by weighing a sample of fish from each tank and then calculating the feed conversion ratios and new feeding rates from this sample. For example, 1,000 fish in a tank have been consuming 10 pounds of feed a day for the last 10 days (100 pounds total). The fish were sampled 10 days earlier and weighed an average of 0.33 pounds or an estimated total of 330 pounds.

Table 6. Recommended stocking and feeding rates for different size groups of tilapia in tanks, and estimated growth rates.

Stocking rate (number/ft3)	Weight (g) Initial	Weight (g) Final	Growth rate (g/day)	Growth period (days)	Feeding rate (%)
225	0.02	0.5-1	-	30	20 - 15
90	0.5-1	5	-	30	15 - 10
45	5	20	0.5	30	10 - 7
28	20	50	1.0	30	7 - 4
14	50	100	1.5	30	4 - 3.5
5.5	100	250	2.5	30	3.5 - 1.5
3	250	450	3.0	70	1.5 - 1.0

A new sample of 25 fish is collected from the tank and weighed. The 25 fish weigh 10 pounds or an average of 0.4 pounds per fish. If this is a representative sample, then 1,000 fish should weigh 400 pounds. Therefore, the change in total fish weight for this tank is 400 minus 330, or 70 pounds. The fish were fed 100 pounds of feed in the last 10 days and gained 70 pounds in weight. Feed conversion then is equal to 1.43 to 1 (i.e., 100 ÷ 70). In other words, the fish gained 1 pound of weight for each 1.43 pounds of feed fed. The daily feeding rate should now be increased to adjust for growth of the fish.

To calculate the new feeding rate, multiply the estimated total fish weight (400 pounds) by the estimated percent body weight of feed consumption for a 0.4-pound fish (from Table 5). Table 5 suggests that the percent body weight consumed per day should be between 2.75 and 3 percent. If 3 percent is used, then 400 times 0.03 is 12.0. Thus, the new feeding rate should be 12 pounds of feed per day for the next 10 days, for a total of 120 pounds. Using this sampling technique the manager can accurately track growth and feed conversion, and base other management decisions on these factors.

Feeding skills

Feeding is the best opportunity to observe overall vitality of the fish. A poor feeding response should be an immediate alarm to the manager. Check all aspects of the system, particularly water quality, and diagnose for diseases if feeding behavior suddenly diminishes.

Fish can be fed once or several times a day. Multiple feedings spread out the waste load on the biofilter and help prevent sudden decreases in DO. Research has shown that small fish will grow faster if fed several times a day. Feeding several times a day seems to reduce problems of feeding dominance in some species of fish. Many recirculating system managers feed as often as every 30 minutes. Multiple feedings at the same location in a tank can increase dominance because a few fish jealously guard the area and do not let other fish feed. In this situation, use feeders that distribute feed widely across the tank. Fish can be fed by hand, with demand feeders, or by automatic feeders, but stationary demand and belt type feeders tend to encourage dominance. Whichever method is used, be careful to evenly distribute feed and **not to overfeed**.

Always purchase high quality feed from a reputable company. Keep feed fresh by storing it in a cool, dry place. Never use feed that is past 60 days of the manufacture date. Never feed moldy, discolored or clumped feed. Molds on feed may produce aflatoxins, which can stress or kill fish. Feed quality deteriorates with time, particularly when stored in warm, damp conditions. A disease known as “no blood” is associated with feed that is deficient in certain vitamins. In a case of “no blood,” the fish appear pale with white gills and blood appears clear, not red. Another nutritional disease known as “broken back syndrome” is caused by a vitamin C deficiency. The only management practice for “no blood” disease and “broken back syndrome” is to discard the feed being used and purchase a different batch or brand of feed.

Fines, crumbled feed particles, are not generally consumed by the fish but add to the waste load of the system, increasing the burden on particulate and biological filters. Therefore, it is recommended that feed pellets be sifted or screened to remove fines before feeding.

Off-flavor

Off-flavor in recirculating systems is a common and persistent problem. Many times fish have to be moved into a clean system, one with clear, uncontaminated water, where they can be purged of off-flavor before being marketed. Purging fish of off-flavor can take from a few days to many weeks (depending on the type and severity of off-flavor). If fish remain in the purging tanks for an extended period, their feeding rate may need to be reduced, or off-flavor may develop within the purging system.

See SRAC Publication No. 431, *Testing Flavor Quality of Preharvest Channel Catfish*, for detailed information on off-flavor.

Stress and disease control

The key to fish management is stress management. Fish can be stressed by changes in temperature and water quality, by handling (including seining and hauling), by nutritional deficiencies, and by exposure to parasites and diseases. Stress increases the susceptibility of fish to disease, which can lead to catastrophic fish losses if not detected and treated quickly. To reduce stress fish must be handled gently, kept under proper water quality conditions, and protected from exposure to poor water quality and diseases. Even sound and light can stress fish. Unexpected sounds or sudden flashes of light often trigger an escape response in fish. In a tank, this escape response may send fish into the side of the tank, causing injury. Fish are generally sensitive to light exposure, particularly if it is sudden or intense. For this reason many recirculating systems have minimal lighting around the fish tanks.

Diseases

There are more than 100 known fish diseases, most of which do not seem to discriminate between species. Other diseases are very host specific. Organisms known to cause diseases and/or parasitize fish include viruses, bacteria, fungi, protozoa, crustaceans, flatworms, roundworms and segmented worms. There are also non-infectious diseases such as brown blood, no blood and broken back syndrome. Any of these diseases can become a problem in a recirculating system. Diseases can be introduced into the system from the water, the fish, and the system’s equipment.

Diseases are likely to enter the system from hauling water, on the fish themselves, or on nets, baskets, gloves, etc., that are moved from tank to tank. Hauling water should never be introduced into the system. Fish should be quarantined, checked for diseases, and treated as necessary. Equipment should be sterilized (e. g., chlorine dip) before moving it between tanks. If possible, provide separate nets and baskets for each tank so they will not contaminate other tanks. Disease can spread rapidly from one tank to another if equipment is freely moved between tanks or if all the water within the system is mixed together as in a common sump, particulate filter or biofilter.

A manager needs to be familiar with the signs of stress and disease which include:

- Excitability
- Flashing or whirling
- Skin or fin sores or discolorations
- Staying at the surface
- Erratic swimming
- Reduction in feeding rate
- Gulping at the surface
- Cessation of feeding
- Mortalities

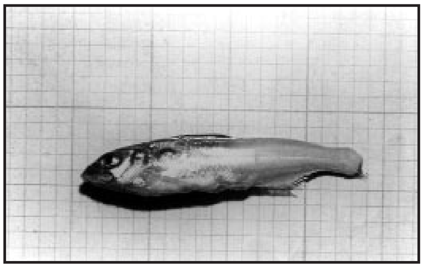
Whenever any of these symptoms appear the manager should check water quality and have a few fish with symptoms diagnosed by a qualified fish disease specialist.

The most common diseases in recirculating systems are caused by bacteria and protozoans. Some diseases that have been particularly problematic in recirculating systems include the protozoal diseases Ich (*Ichthyophthirius*) and *Trichodina*, and the bacterial diseases columnaris, *Aeromonas, Streptococcus* and *Mycobacterium*. It appears that *Trichodina* and *Streptococcus* diseases are problematic in recirculating systems with tilapia, while *Mycobacterium* has been found in hybrid striped bass in intensive recirculating systems.

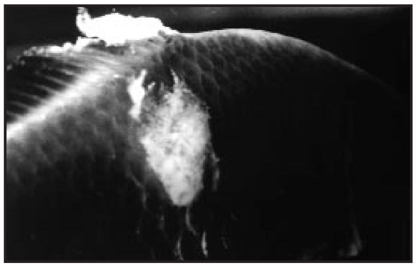
It may be possible to treat diseases with chemicals approved for fish (see SRAC Publication No. 410, *Calculating Treatments for Ponds and Tanks*), although few therapeutants are approved for use on food fish species other than catfish and rainbow trout. Treatment always has its problems. In the case of recirculating systems, chemical treatments can severely disrupt the biofilter. Biofilter bacteria are inhibited to some degree by formalin, copper sulfate, potassium permanganate, and certain antibiotics. Even sudden changes in salt concentration will decrease biofilter efficiency. If the system is designed properly, it may be possible to isolate the biofilter from the rest of the system, treat and flush the fish tanks, and then reconnect the biofilter without exposing it to chemical treatment. However, there is a danger that the biofilter will reintroduce the disease organism. Whenever a chemical treatment is applied, be prepared to exchange the system water and monitor the DO concentration and other water quality factors closely. Fish usually reduce their feed consumption after a chemical treatment; therefore, feeding rates need to be monitored carefully.

Tables 7 and 8 give possible causes and management options based on the observation of the fish or water quality tests.

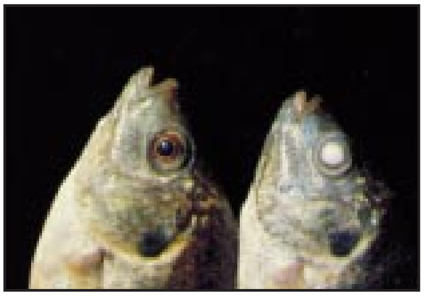
Examples of fish diseases



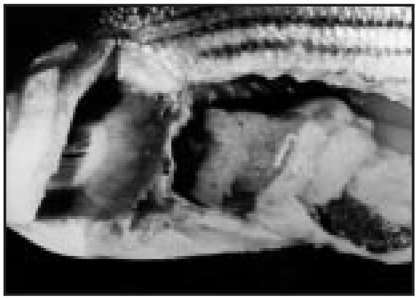
A–Columnaris



B–*Aeromonas*



C–*Streptococcus*
(cataract and pop-eye)



D–*Mycobacterium*
(granular liver and spleen)

Conclusions

Recirculating systems have developed to the point that they are being used for research, for ornamental/tropical fish culture, for maturing and staging brood fish, for producing advanced fry/fingerlings, and for producing food fish for high dollar niche markets. They continue to be expensive ventures which are as much art as science, particularly when it comes to management. Do your homework before deciding to invest in a recirculating system. Investigate the efficiency, compatibility and maintenance requirements of the components. Estimate the costs of building and operating the system and of marketing the fish without any return on investment for at least 2 years. Know the species you intend to grow, their environmental requirements, diseases most common in their culture, and how those diseases are treated. Know your potential markets and how the fish need to be prepared for that market. Be realistic about the

Table 7. Possible options in managing a recirculating tank system based on observations of the fish.

Observation	Possible cause	Possible management
Fish:		
Excitable/darting/erratic swimming	■ excess or intense sounds/lights	reduce sound level/pad sides of tank/reduce light intensity
	■ parasite	examine* fish with symptoms
	■ high ammonia	check ammonia concentration
Flashing/whirling	■ parasite	examine fish with symptoms
Discolorations/sores	■ parasite/bacteria	examine fish with symptoms
Bloated/eyes bulging out	■ virus or bacteria	examine fish with symptoms
	■ gas bubble disease	check for supersaturation and examine fish with symptoms
Lying at surface/not swimming off	■ parasite	examine fish with symptoms
	■ low oxygen	check dissolved oxygen in tank
	■ high ammonia or nitrite	check ammonia and nitrite concentrations
	■ bad feed	check feed for discoloration/clumping and check blood of fish
	■ high carbon dioxide	check carbon dioxide level
Crowding around water inflow/aerators	■ low oxygen	check dissolved oxygen in tank
	■ parasite/disease	examine fish with symptoms
	■ high ammonia or nitrite	check ammonia and nitrite concentrations
	■ bad feed	check feed for discoloration/clumping and check blood of fish
Gulping at surface	■ low oxygen	check dissolved oxygen in tank
	■ parasite/disease	examine fish with symptoms
	■ high ammonia or nitrite	check ammonia and nitrite concentrations
	■ high carbon dioxide	check carbon dioxide level
	■ bad feed	check feed for discoloration/clumping and check blood of fish
Reducing feeding	■ low oxygen	check dissolved oxygen in tank
	■ parasite/disease	examine fish with symptoms
	■ high ammonia or nitrite	check ammonia and nitrite concentrations
	■ bad feed	check feed for discoloration/clumping and check blood of fish
Stopping feeding	■ low oxygen	check dissolved oxygen in tank
	■ parasite/disease	examine fish with symptoms
	■ high ammonia or nitrite	check ammonia and nitrite concentrations
Discolored blood – Brown	■ high nitrite	examine fish with symptom; add 5 to 6 ppm chloride for each 1 ppm nitrite; purchase new feed and discard old feed
Clear (no blood)	■ vitamin deficiency	examine fish with symptom; check feed for discoloration/clumping; purchase new feed and discard old feed
Broken back or “S” shaped backbone	■ vitamin deficiency	examine fish with symptom; purchase new feed and discard old feed

*Have fish examined by a qualified fish diagnostician.

money, time and effort you are willing to invest while you are in the learning curve of managing a recirculating system.

Finally, design the system with an emergency aeration system, backup power sources, and backup system components. Monitor water quality daily and maintain it within optimum ranges.

Exclude diseases at stocking. Perform routine diagnostic checks and be prepared to treat diseases. Reduce stress whenever and however possible. STAY ALERT!

Table 8. Possible management options based on water quality and feed observations.

Observation	Possible management
Low dissolved oxygen (less than 5 ppm)	■ increase aeration ■ stop feeding until corrected ■ watch for symptoms of new parasite/disease
High carbon dioxide (above 20 ppm)	■ add air stripping column ■ increase aeration ■ watch for symptoms of new paraside/disease
Low pH (less than 6.8)	■ add alkaline buffers (sodium bicarbonate, etc.) ■ reduce feeding rate ■ check ammonia and nitrite concentarations
High ammonia (above 0.05 ppm as un-ionized)	■ exchange system water ■ reduce feeding rate ■ check biofilter, pH, alkalinity, hardness, and dissolved oxygen in the biofilter ■ watch for symptoms of new parasite/disease
High nitrite (above 0.5 ppm)	■ exchange system water ■ reduce feeding rate ■ add 5 to 6 ppm chloride per 1 ppm nitrite ■ check biofilter, pH, alkalinity, hardness, and dissolved oxygen in the biofilter ■ watch for symptoms of new parasite/disease
Low alkalinity	■ add alkaline buffers
Low hardness	■ add calcium carbonate or calcium chloride
Discolored/clumped feed	■ purchase new feed and discard old feed ■ watch for symptoms of new parasite/disease

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Recirculating Aquaculture Tank Production Systems

A Review of Component Options

Thomas M. Losordo[1], Michael P. Masser[2] and James E. Rakocy[3]

There is a great deal of interest in recirculating aquaculture production systems both in the United States and worldwide. Most fish grown in ponds, floating net pens, or raceways can be reared in commercial scale recirculating systems, but the economic feasibility of doing so is not certain. Recirculating systems are generally expensive to build, which increases production cost. (For more information see SRAC publication 456 on the economics of recirculating systems). The challenge to designers of recirculating systems is to maximize production capacity per dollar of capital invested. Components should be designed and integrated into the complete system to reduce cost while maintaining or even improving reliability.

Research and development in recirculating systems has been going on for nearly three decades. There are many alternative technologies for each process and operation. The selection of a particular technology depends upon the species being reared, production site infrastructure, production management expertise, and other factors. Prospective users of recirculating aquaculture production systems need to know about the required water treatment processes, the components available for each process, and the technology behind each component. This publication is intended as a starting point for such a study.

A recirculating system maintains an excellent cultural environment while providing adequate feed for optimal growth. Maintaining good water quality is of primary importance in aquaculture. While poor water quality may not be lethal to the crop, it can reduce growth and cause stress that increases the incidence of disease. Critical water characteristics include concentrations of dissolved oxygen, un-ionized ammonia-nitrogen, nitrite-nitrogen, and carbon dioxide. Nitrate concentration, pH, alkalinity and chloride levels also are important.

The by-products of fish metabolism include carbon dioxide, ammonia-nitrogen, and particulate and dissolved fecal solids. Water treatment components must be designed to eliminate the adverse effects of these waste products. In recirculating tank systems, proper water quality is maintained by pumping tank water through special filtration and aeration or oxygenation equipment. Each component must be designed to work in conjunction with other components of the system. For more information on water quality requirements and management of recirculating systems, see SRAC publications 451 and 452.

Waste solids removal

The decomposition of solid fish waste and uneaten or indigestible feed can use a significant amount of oxygen and produce large quantities of ammonia-nitrogen. There are three categories of waste solids—settleable, suspended, and fine or dissolved solids.

Settleable solids

Settleable solids are generally the easiest to deal with and should be removed from the culture tank water as rapidly as possible. This is easiest when bottom drains are properly placed. In tanks with circular flow patterns (round, octagonal, hexagonal, square with rounded corners) and minimal agitation, settleable solids can be removed as they accumulate in the bottom center of the tank, in a separate, small flow-stream of water, or together with the entire flow leaving the tank. Center drains with two outlets are often

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used for the small flow-stream process. This double drain divides the flow leaving the tank into a small pipe carrying the settleable solids, and a larger pipe with a higher flow rate carrying the suspended solids from the upper water column of the tank (Fig. 1).

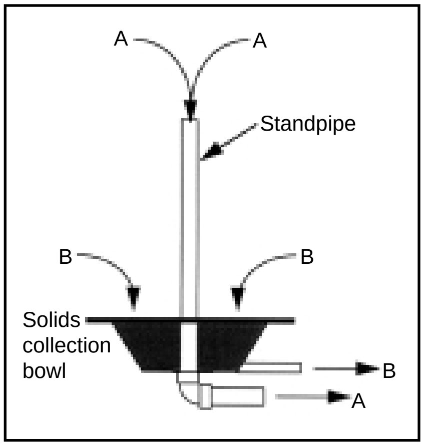

Figure 1. Typical double drain for removing settleable solids from a fish culture tank; A = suspended solids flow stream, B = settleable solids flow stream. (after Losordo, 1997).

Settled solids should be removed from the center of the tank on a continuous or semi-continuous basis. The flow rate at which the settleable solids are carried will determine the method used to collect and concentrate them for further treatment or disposal. In systems with a high settleable solids flow rate (20 to 50 percent of the total tank flow), swirl separators, settling basins, or drum screen filters are used to collect these solids. At lower flow rates, smaller settling components can be used. An example is a double drain developed by Waterline, Inc.[1] (Prince Edward Island, Canada). In this patented design, the flow containing settleable solids moves slowly though a pipe (under the tank) leading to an external standpipe (water level control structure). The flow velocity is slow enough that the solids settle out within the pipe while the clearer water overflows the standpipe. The external stand pipe is routinely removed to increase the water velocity in the pipe and the settled solids are flushed from the line.

Another example of a double drain is a particle trap developed at the Center for Scientific and Industrial Research (SINTEF), Norwegian Hydrotechnical Laboratory, in Trondheim, Norway.

In this design, settleable solids flow under a plate, spaced just slightly off the bottom of the tank, in a flow of water that amounts to only 5 percent of the total flow leaving the center of the tank (Flow B, Fig. 2). The larger flow (95 percent of the total) exits the tank through a large discharge strainer mounted at the top of the particle trap (Flow A, Fig. 2). Outside of the tank, the settleable solids flow-stream from the particle trap enters a sludge collector (Flow B, Fig. 3). The waste particles settle and are retained in the sludge collector, and the clarified water exits the sludge collector at the top and flows by gravity for further treatment. The sludge in the collector, which has an average dry weight solids content of 6 percent, is drained from the bottom of the collector.

In rectangular raceways with plug flow (flow that moves along the long axis of the raceway tank), solids are more difficult to remove as the velocity at the bottom of the tank is generally slower than in round tanks. If the water velocity at the tank bottom can be increased to move the settled solids along the bottom of the tank, then solids can be removed using a sediment trap. The sediment trap should span the bottom, across the short axis of the raceway, perpendicular to the direction of water flow. Two reviews of tank flow and hydraulic analysis can be found in Burley and Klapsis (1988) and Tvinnereim (1988).

An alternative to plug flow within a raceway is to create a completely mixed (horizontally and vertically) tank by installing a water inlet and outlet manifold along the long axis of the tank. As seen in Figure 4, water enters uniformly along the bottom of one side of the raceway and is removed along the other side. Water must enter at a high enough velocity to create a rotational flow along the short axis of the raceway (Fig. 4). The solids will move across the bottom of the raceway and into the effluent manifold.

Another method of dealing with settleable solids is to keep them in

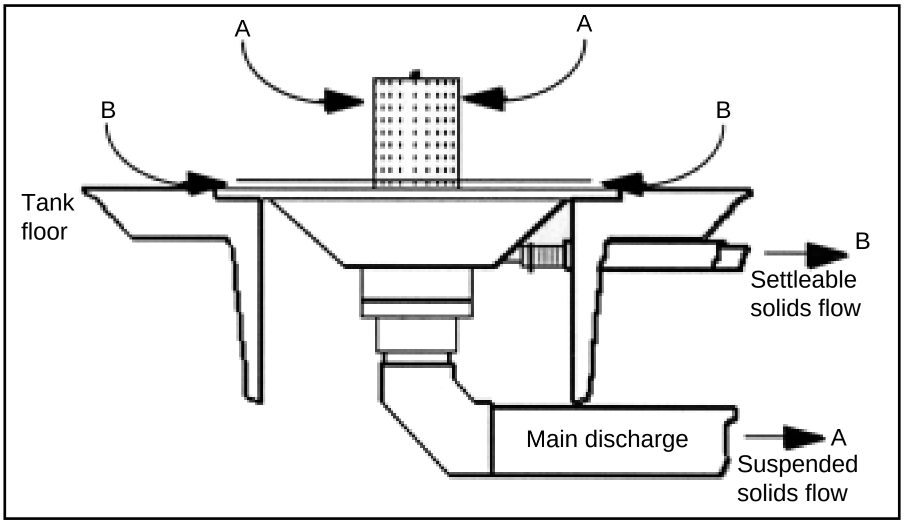

Figure 2. The ECO-TRAP™ particle trap is an advanced double drain design that concentrates much of the settleable solids in only 5 percent of the water flow leaving the fish culture tank (B). (after Hobbs et al., 1997). (ECO-TRAP is a trademark of AquaOptima AS, Pir Senteret, 7005 Trondheim, Norway, U.S. Patent No. 5,636,595.)

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[1] Mention of a specific product or tradename does not constitute and endorsement by the authors or the USDA Southern Regional Aquaculture Center, nor does it imply approval to the exclusion of other suitable products.

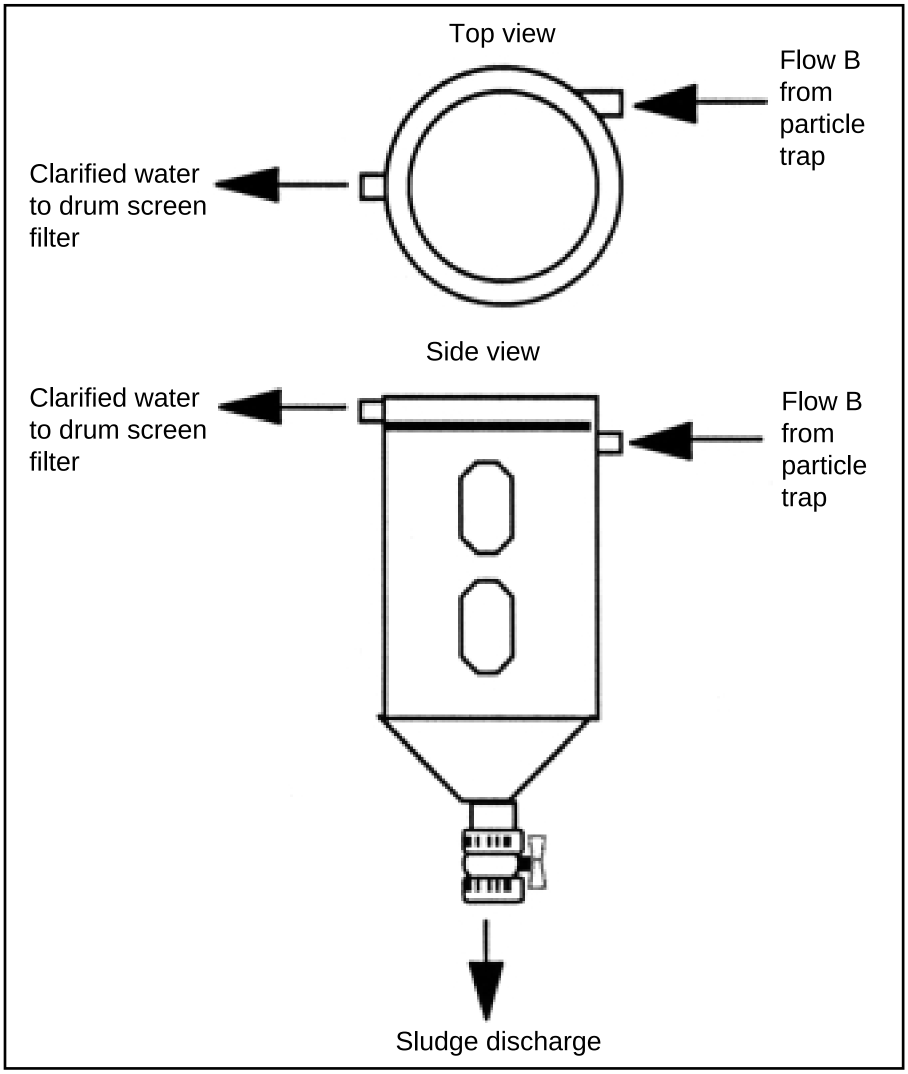

Figure 3. The sludge collector that works in conjunction with the ECO-TRAP™ to remove settled solids from the flow stream B (Fig. 2) (after Hobbs et al., 1997).

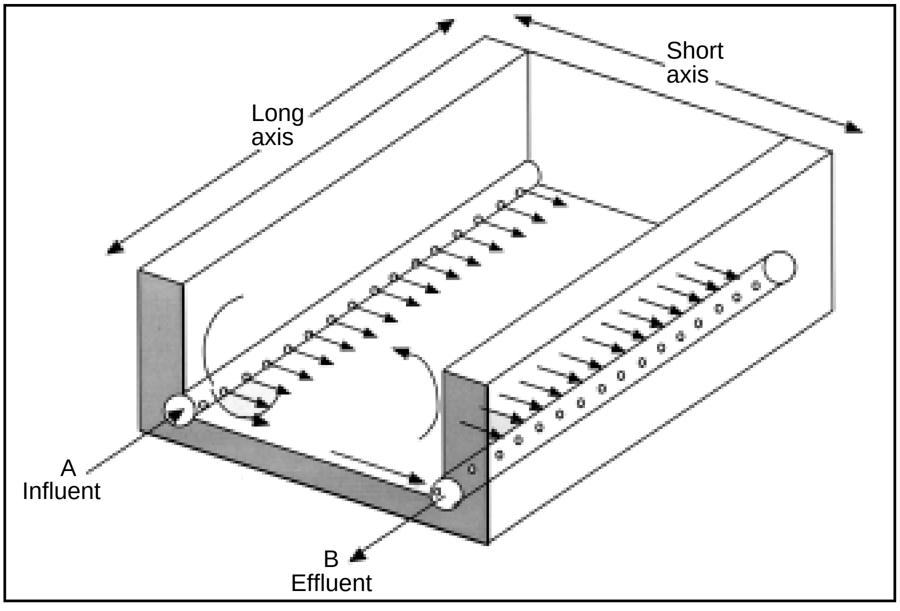

Figure 4. Cross-section of a "cross-flow" raceway. Water flows in through an inlet manifold with jets (A) and out through a similar drain manifold (B) on the opposite side of the tank (after Colt and Watten, 1988).

suspension with continuous agitation until they enter an external settling tank. In settling tanks (or basins), water flow is very slow so that solids settle out by gravity. Settling tanks may or may not include tube or lamella sedimentation material. This material is constructed with bundles of tubes or plates, set at specific angles to the horizontal (usually 60º), that reduce both the settling distance and circulation within the settling tank. Using settling plates reduces the size requirement of a settling basin, thus saving space within a facility. However, the plates make routine cleaning of settling basins more time-consuming.

The benefits of using external settling basins outside of the rearing tank are simplicity of operation, low energy requirements, and the generally low cost of construction. The disadvantages include the relatively large size of settling basins, the time used in routine cleaning, and the large quantity of water that is wasted in the cleaning process. If settling basins are not cleaned regularly, waste solids can break down within the basin and contribute to the ammonia-nitrogen production and oxygen demand of the system.

Another way to remove settleable solids, external to the culture tank, is to use a centrifugal settling component known as a hydrocyclone or swirl separator. In this design, water and particulate solids enter the separator tangentially, creating a circular or swirling flow pattern in a conical shaped tank. The heavier solids move towards the walls and settle to the bottom where they are removed continuously. The main advantage of these units is the compact size. A major disadvantage is the large volume of replacement water required because of the continuous stream of wastewater.

Suspended solids

From an engineering viewpoint, the difference between suspended solids and settleable solids is a practical one. Suspended solids will not easily settle out of the water column in the fish culture tank. Suspended solids are not always dealt with adequately in recirculating systems. Most current technologies for removing suspended solids generally involve some form of mechanical filtration. Two types of mechanical filtration are screen filtration and expandable granular media filtration.

Screen filtration: Screen filters use some form of fine mesh material (stainless steel or polyester) through which effluent passes while the suspended solids are retained on the screen. Solids are usually removed from the screen by rotating the clogged screen surface past high pressure jets of water. The solids are carried away from the screen in a small stream of waste water. The feature that makes each screen filter different and the challenge in designing these units is the process of collecting the solids on the mesh surface. The screening material has been used in a disk configuration (Fig. 5A), drum screen configuration (Fig. 5B), and incline belt configuration (Fig. 5C).

In rotating disk filters, water to be treated enters one end of the filter unit and must pass through sequential vertical disks within the filter. A problem with this design is the small amount of screen surface on which to capture solids. In heavily fed production systems, solids can build up so heavily on one side of the filter that the screens collapse from the water pressure.

The most common screen filter is the drum filter (Figs. 5B and 6). With this configuration, water enters the open end of a drum and passes through a screen attached to the circumference of the drum.

In most installations, the drum rotates only when the filter mesh becomes clogged with solids, and a high pressure jet of water (from the outside of the drum) washes the solids off the screen and into an internal collection trough leading to a waste drain. The advantage of the drum screen filter configuration over the single plate disk filter is the larger surface area of the drum for comparably sized units.

The main advantage of using screen filter technology rather than settling basins and swirl separators is their small size and relatively low water loss during backwashing. Libey (1993) reported that, on average, in a tilapia system, only 13.4 percent of the water used with a settling basin was needed with a drum screen filter.

The main disadvantage of commercial screen filters is cost, especially for smaller units. The smallest commercially available units can process approximately 475 liters per minute (125 gpm) loaded with 25 mg/L of suspended solids, and cost about $6,000. A 100 percent increase in processing capacity increases the cost of a unit by about 50 percent (a unit to process 950 liters/minute costs about $9,000). So, larger units are more cost effective. To take advantage of this, the flow streams from several production tanks can be combined into one treatment stream that is cleaned by a larger drum screen filter. However, the advantage of the economy of scale must be weighed against the risk of spreading disease and water quality problems within linked fish production tanks.

Vacuum cleaned drum screen filters are now in use. These units have limited capacity (375 to 1,800 L/ minute, 100 to 475 gpm) and their performance in commercial facilities has not been well documented. Incline screen or belt screen filters also are beginning to

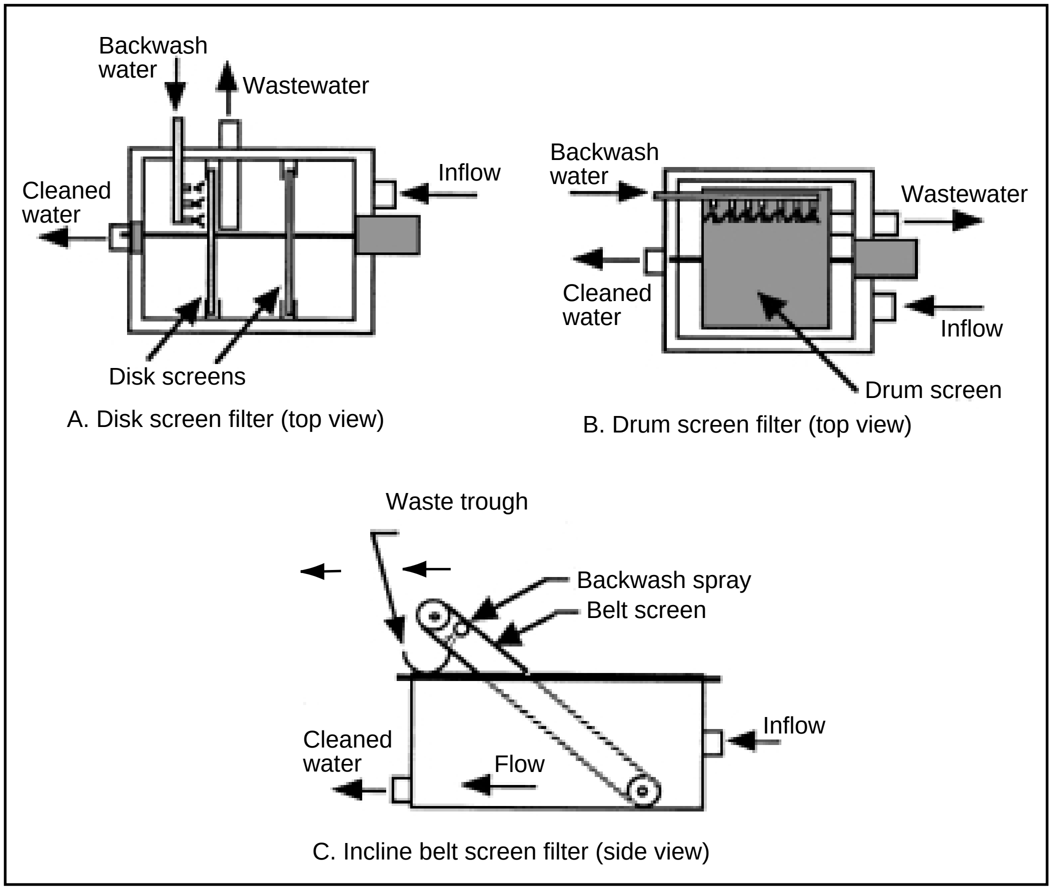

Figure 5. Three screen filter configurations used in recirculating tanks to capture and remove suspended solids.

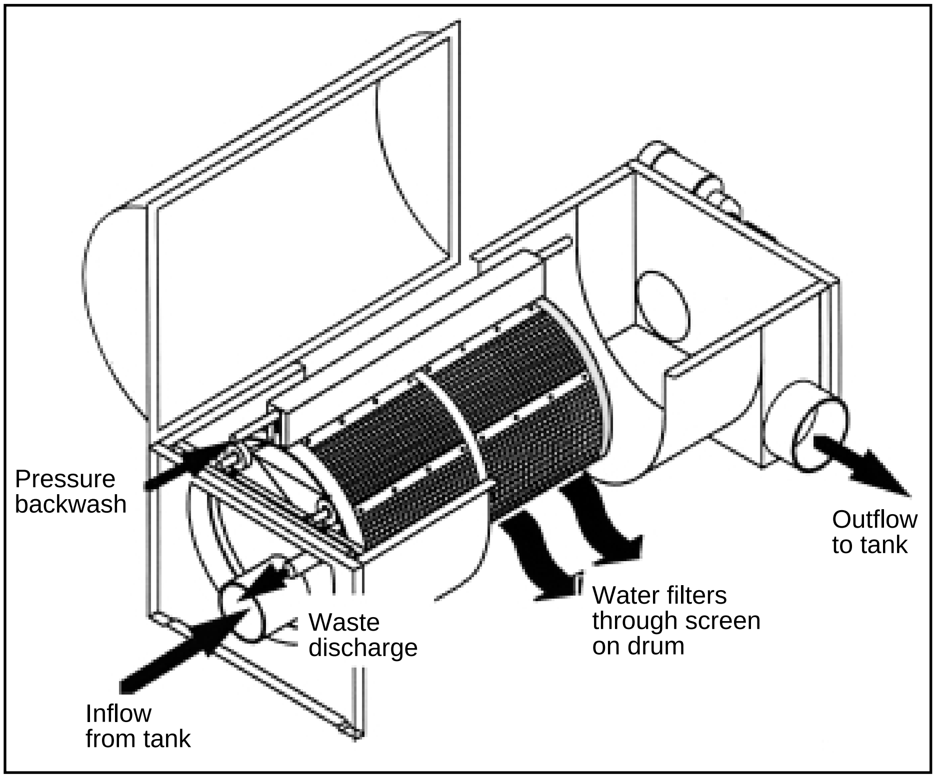

Figure 6. Typical drum screen filter (shown with a cut-away and expanded midsection) for waste solids removal from aquacultural recycle flow streams. (Drawing provided by and used with permission of PRA Manufacturing, Nanaimo, B.C.)

be used in the aquaculture industry (Fig. 5). These units resemble conveyor belts placed on an incline. Water passes through the screen where suspended solids are retained; solids are lifted out of the water on the incline screen and sprayed off with high pressure water in a cleaning process similar to that of disc and drum screen filters. The units manufactured currently have flow capacities in excess of 7,500 liters per minute (1980 gpm). There is little data on the operational characteristics of these filters.

Expandable granular media filtration: Expandable granular media filters remove solids by passing water through a bed of granular medium (sand or plastic beads). The solids either adhere to the medium or are trapped within the open spaces between the medium particles. Over time, the filters will become clogged with solids and require cleaning, or backwashing. Backwashing these filters requires that the filter bed be expanded (from a compacted state) to release the solids. For other applications (e.g., drinking water, swimming pools), the most common filtration medium is sand. Pressurized down-flow sand filters have been widely used in hatchery operations. While these filters can remove much of the suspended solids in a flow-stream, when fish are fed heavily the filter must be backwashed frequently, which wastes a lot of water. Backwashing these filters is accomplished by reversing the flow of water through the filter medium, causing the bed to expand or “boil.” This releases trapped solids and scrapes bacterial growth off the filter medium. However, bacterial growth on the sand eventually creates gelatinous masses within the filters that are impossible to clean with simple backwashing. Then it is necessary to open and manually clean the filter. Down-flow sand filters reduce or stop the flow of water when they clog. Even short-term interruptions of water flow can be disastrous to intensive recirculating systems.

An alternative design, used successfully in the U.S., uses floating plastic beads instead of sand.

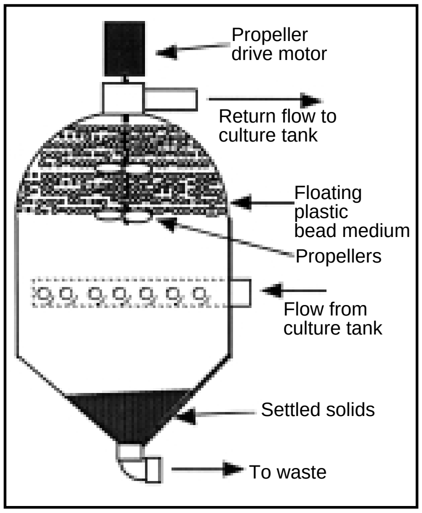

Figure 7. The propeller washed bead filter traps waste solids between the beads and backwashes by expanding the bed of beads with a propeller. (U.S. Patent No. 5,126,042 by Dr. Ronald Malone, Dept. of Civil Engineering, Louisiana State University)

These low density, floating plastic beads trap and remove suspended solids from the flow-stream as the water passes up through a bed of beads (Fig. 7).

The solids are removed by activating a motor that turns a propeller located within the bed of beads. The propeller expands the bed of beads and releases the waste solids that are trapped within it. After the bed expansion period, a short settling period allows the beads to re-float and the solids to settle to the bottom of the filter chamber. A valve is then opened and the settled solids are removed. This sequence of events can be automated with electronic circuits and automated valves. Another bead filter design, referred to as the “bubble washed” bead filter, eliminates the requirement for a propeller to backwash the filter bed. This filter resembles an “hour glass” with two chambers connected by a narrow “washing throat” (Fig. 8).

In the filtration mode, water passes up through the beads while they are in the upper filtration chamber. When the beads need cleaning, the flow is stopped and the filter is drained so that the filter medium drops through the

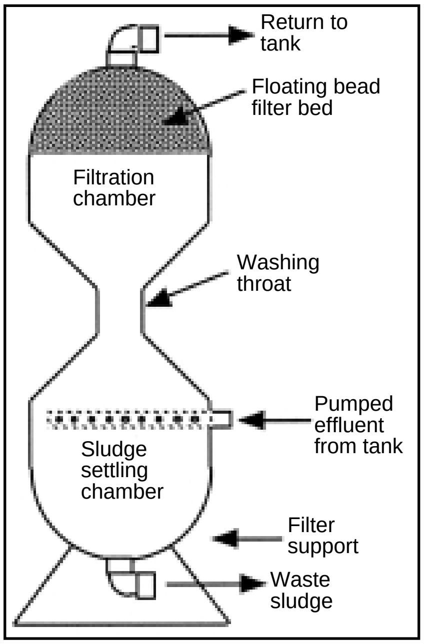

Figure 8. The bubble bead filter operates much like the propeller washed bead filter, except that it backwashes by dropping the filtration medium by gravity through a washing throat. (U.S. Patent No. 5,232,586 by Dr. Ronald Malone, Dept. of Civil Engineering, Louisiana State University)

"washing throat" into the sludge settling chamber. When the flow is re-started, the filter medium floats back into the filter chamber and the waste sludge settles to the bottom of the settling chamber ready for discharge to a waste drain.

The advantage of bead filters is the compact size of the unit and low water use during backwashing. Once biologically active, the beads become sticky and can remove even fine suspended solids. The bacteria that make the filter sticky are a combination of autotrophic and heterotrophic bacteria. The autotrophic bacteria contribute to nitrification. The heterotrophic bacteria break down the organic solids that are trapped within the bead bed. This can be a disadvantage, because during the time between backwashings (1 to 48 hours), solids undergoing bacterial degradation use oxygen from the system water and release ammonia-nitrogen. The oxygen consumed by these bacteria needs to be replaced and the ammonia-nitrogen produced must be treated.

Fine and dissolved solids

Many of the fine suspended solids and dissolved organic solids that build up within intensive recirculating systems cannot be removed with traditional mechanisms. A process called foam fractionation (also referred to as air-stripping or protein skimming) is often employed to remove and control the build-up of these solids. Foam fractionation is a general term for a process in which air introduced into the bottom of a closed column of water creates foam at the surface of the column. Foam fractionation removes dissolved organic compounds (DOC) from the water column by physically adsorbing DOC on the rising bubbles. Fine particulate solids are trapped within the foam at the top of the column, which can be collected and removed. The main factors affected by the operational design of the foam fractionator are bubble size and contact time between the air bubbles and the DOC. A counter-current design (bubbles rising against a downward flow of water) improves efficiency by lengthening the contact time between the water and the air bubbles (Fig. 9). In this design, water is injected into the foam fractionator through a venturi. The venturi mixes air with the water and the air / water mixture enters the body of the foam fractionator tangentially.

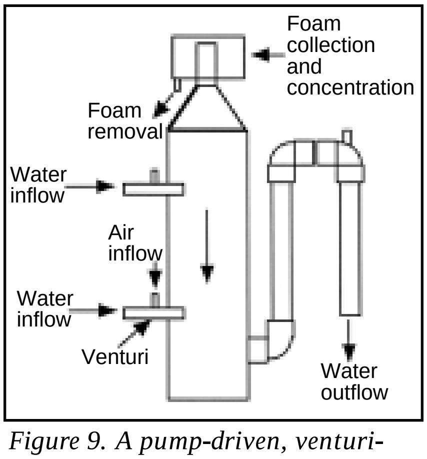

Figure 9. A pump-driven, venturi-type foam fractionator design. A water/air mixture is injected tangentially into the foam fractionator (after Losordo, 1997).

Ammonia and nitrite-nitrogen control

Controlling the concentration of un-ionized ammonia-nitrogen (NH_3) in the culture tank is a primary design consideration in recirculating systems. Ammonia-nitrogen (a by-product of the metabolism of protein in feeds) must be removed from the culture tank at a rate equal to the rate it is produced to maintain a stable and acceptable concentration. In systems with external ammonia-nitrogen treatment processes, the efficiency of the ammonia-nitrogen removal process will dictate the recirculating flow rate (e.g., a less efficient removal system will require a higher recycle flow rate from the tank through the filter). There are a number of methods for removing ammonia-nitrogen from water: air stripping, ion exchange, and biological filtration. Air stripping of ammonia-nitrogen through non-flooded (no standing water in the reactor) packed columns requires that the pH of the water be adjusted to above 10 and readjusted to safe levels (7 ro 8) before the water re-enters the culture tank. Ion exchange technology is costly and requires a mechanism for "wasting" ammonia-laden salt water. A salt-brine is used to "regenerate" the filter by removing ammonia-nitrogen from the resin (filter medium) once it becomes saturated with ammonia-nitrogen.

Biological filtration is the most widely used method. In biological filtration (or biofiltration), there is a substrate with a high specific surface area (large surface area per unit volume) on which the nitrifying bacteria can attach and grow. Ammonia and nitrite-nitrogen in the recycled water are oxidized (converted) to nitrite and nitrate by *Nitrosomonas* and *Nitrobacter* bacteria, respectively. Commonly used biofilter substrates include gravel, sand, plastic beads, plastic rings, and plastic plates. The most common biofiltration technologies are discussed below.

Rotating biological contactor

Rotating biological contactors (RBC) have been used in the treatment of domestic wastewater for decades, and are now widely used as nitrifying filters in aquaculture applications. RBC technology is based on the rotation of a biofilter medium attached to a shaft, partially submerged in water. Approximately 40 percent of the substrate is submerged in the recycle water (Fig. 10). Nitrifying bacteria grow on the medium and rotate with the RBC, alternately contacting the nitrogen-rich water and the air. As the RBC rotates, it exchanges carbon dioxide (generated by the bacteria and fish) for oxygen from the air. The tangential velocity of the outer edge of the RBC should be about 35 to 50 feet per minute. For example, an RBC with a diameter of 4 feet would rotate at 3 to 4 revolutions per minute (rpm). The advantages of RBC technology are simplicity of operation, the ability to remove carbon dioxide and add dissolved oxygen, and a self-cleaning capacity. Major disadvantages are the high capital cost and mechanical instability. Poorly designed or built RBCs can break down mechanically with the weight of the biological growth on the filter medium. RBCs also have been designed to be turned by water (similar to a water wheel) and compressed air.

In early aquaculture applications, RBCs had simple discs cut from corrugated fiberglass plate. Now they use media with high specific surface area, such as plastic blocks or a polyethylene tubular medium (resembling hair curlers). These newer plastic media remove more ammonia, nitrite-nitrogen and carbon dioxide in small RBC units. The plastic media have specific surface areas of up to 200 m^2/m^3 (69 ft^2/ft^3). In aquaculture applications, volumetric nitrification rates of approximately 76 g TAN/m^3 per day can be expected with this type of biological filter (Wheaton et al., 1994). When including these filters in a recirculating system as a nitrifying filter component (assuming 2.5 percent of the feed becomes TAN), a design criterion of 3.6 kg feed/day/m^3 of medium should be used (0.189 pounds/day/ft^3 of medium).

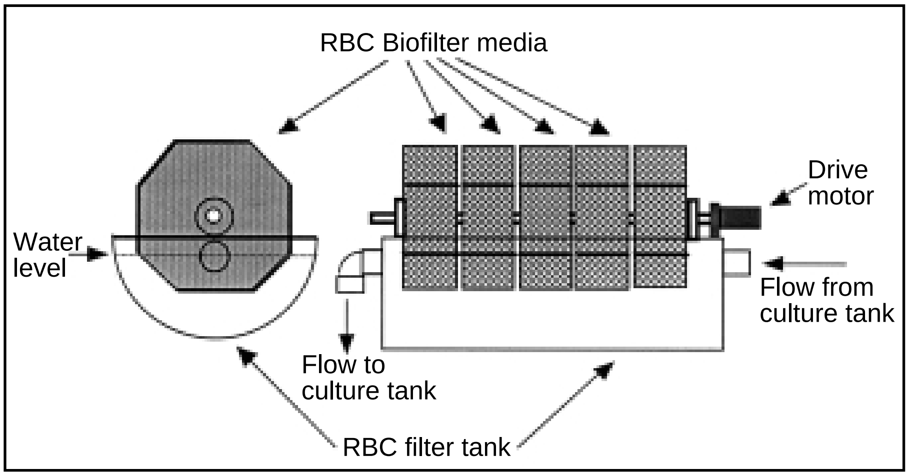

Figure 10. A rotating biological contactor unit powered by an electric gear motor.

The filter medium increases in weight as much as 10 fold during operation, so the support structure must accommodate the additional weight.

Trickling filters

Trickling filters used in aquaculture systems have evolved from those used in domestic sewage treatment. This type of filter consists of a water distribution system at the top of a reactor filled with a medium that has a relatively low specific surface area, generally less than 330 m^2/m^3 (100 ft^2/ft^3). This creates large void (air) spaces within the filter medium (Fig. 11). As these filters are operated in a non-flooded configuration, they provide nitrification, aeration, and some carbon dioxide removal in one unit. (The term non-flooded is used to indicate

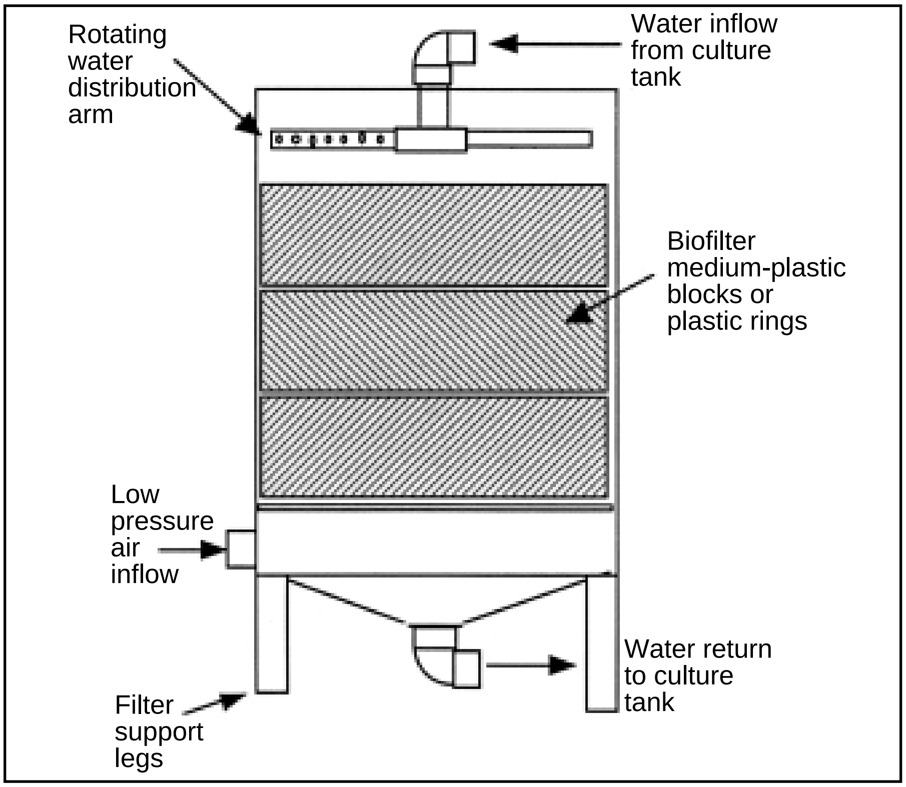

Figure 11. Trickling filters are non-submerged biological filters in which the water is evenly distributed over the medium.

that the biological filter medium is not completely submerged in water). The flow rate through trickling filters is limited by the void space through which water can pass. In general, packing media with more void space can pass a higher rate of flow per square meter of (top) cross sectional surface area. The main disadvantage of trickling filters is that they are relatively large and biofilter media are expensive. Also, if the recycled water is not prefiltered to remove suspended solids, trickling filters can become clogged over time. As with RBC media, the weight of the biological growth on the filter media should be considered in designing the support structure.

Volumetric nitrification rates of approximately 90 g TAN / m^3 per day can be expected with this type of biological filter (Losordo, unpublished data). When designing these filters into a recirculating system as a nitrifying filter component (assuming 2.5 percent of the feed becomes TAN), a design criteria of 3.6 kg feed / day / m^3 of medium should be used (0.225 pound / day / ft^3 of medium).

Expandable media filters

The expandable media floating bead filters described in the previous section (Figs. 7 and 8 are also used as biofilters in some aquaculture applications. Generally operated as upflow filters, the beads have a high specific surface area on which nitrifying bacteria can colonize. The major advantage of this technology is the combination of nitrification and the solids removal processes into one component. The disadvantage, as noted before, is that solids are held in a place where they can degrade and affect the system's water quality. In general, using these filters will require the designer to provide for more oxygenation and biofiltration capacity. The plastic bead medium used in these filters has a specific surface area of 1,150 to 1,475 m^2 / m^3 (350 to 450 ft^2 / ft^3). Volumetric nitrification rates of approximately 325 g TAN / m^3 / day can be expected with this type of biological filter (Beecher et al., 1997). When designing these filters into a recirculating system as a nitrifying and solids removal component (assuming 2.5 percent of the feed becomes TAN), a design criterion of 13 kg of feed / day / m^3 of medium should be used (0.81 pounds / day / $ft.^3$ of medium; the manufacturer recommends a design rate of 1.0 pound / day / ft^3).

Fluidized bed filters

Fluidized bed filters are essentially sand filters operated continuously in the expanded (backwash) mode. Water flows up through a bed of sand at a rate sufficient to lift and expand (fluidize) the bed of sand and keep the sand particles in motion so that they no longer are in continuous contact with each other (Fig. 12). Fluidized bed filters use sand of smaller diameter than that used in particulate solids removal applications. Plastic beads with densities slightly greater than water also have been used successfully in fluidized bed filters. A fluidized bed filter is an excellent environment for the growth of nitrifying bacteria, and bacteria can colonize the entire surface area of the filter medium. The turbulent environment also keeps the bacteria sheared from the medium so that the filter is self-cleaning. The main advantage of fluidized bed technology is the high nitrification capacity in a relatively compact unit. The sand also is extremely low cost. Fluidization (pumping) requirements depend upon the size and weight of the medium being used. Keep in mind that the buoyancy of the medium changes with the amount of biological growth on the medium. This, in turn, depends upon the water temperature, nutrient loading rate, and degree of bed fluidization.

Unless there is a system for recovering sand as water leaves the filter, the medium will need to be replaced routinely. Depending upon the temperature, nutrient concentration and size of the medium (and assuming 2.5 percent of the feed becomes TAN), a design criterion of 20 to 40 kg of feed / day / m^3 of medium should be used (1.25 to 2.5 pounds / day / ft^3 of medium).

Mixed bed reactors

Mixed bed reactors are a new and interesting cross between upflow plastic bead filters and fluidized bed reactors. These filters use a plastic medium kept in a continuous state of movement (Fig. 13). The diameter of the plastic medium is usually much larger than sand, so it has a lower specific surface area (800 to 1,150 m^2 / m^3; 240 to 350 ft^2 / ft^3). The beads are usually neutrally buoyant or just slightly heavier than water. The plastic beads are usually mixed by mechanical or hydraulic means. Mixed bed filters are

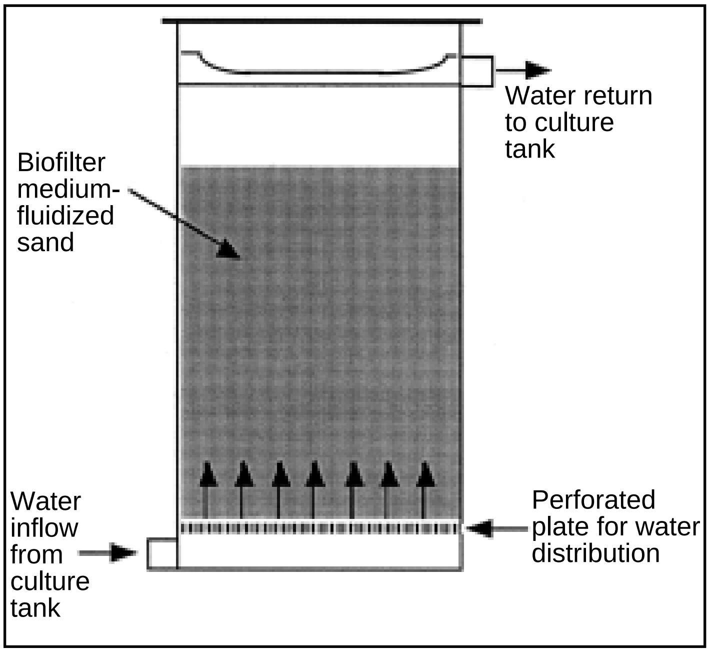

Figure 12. A simplified view of a fluidized sand bed biological filter.

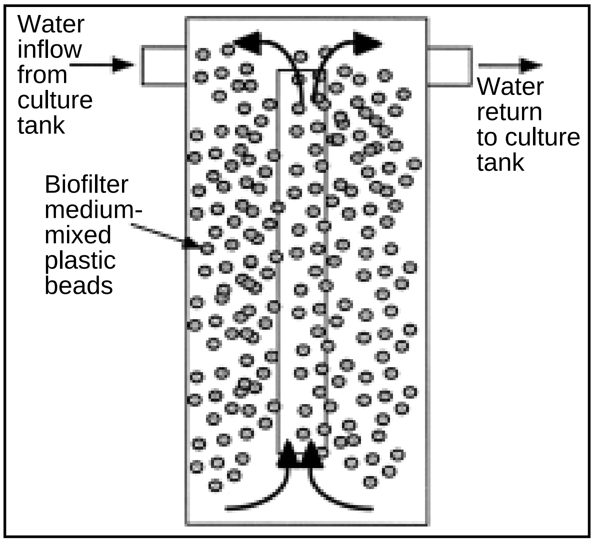

Figure 13. A common configuration for a mixed bed reactor biological filter.

designed as up-flow or down-flow filters and, like fluidized bed filters, they generate biological solids but will not clog because of the continuous movement of the medium. The plastic medium moves through a pipe within the main reactor to vertically mix the bead bed. Depending upon the nutrient concentration and medium size (and assuming 2.5 percent of the feed becomes TAN), a design criterion of 16 to 23 kg of feed/day/m^3 of medium should be used (1.0 to 1.4 pounds/day/ft^3 of medium).

Dissolved gas

Recirculating systems should maintain adequate dissolved oxygen (DO) concentrations of at least 6 mg/L and keep carbon dioxide (CO_2) concentrations at less than 25 mg/L for best fish growth. Colt and Watten (1988) and Boyd and Watten (1989) discuss aeration and oxygenation systems used in aquaculture; a summary of the component options follows.

The term **aeration** is used here to refer to the dissolution of oxygen from the atmosphere into water. The transfer of pure oxygen gas to water is referred to as **oxygenation**.

Aeration

Diffused aeration: Adding oxygen to a recirculating system by aerating only the water flowing into the culture tank will not usually supply an adequate amount of oxygen for fish production. The amount of oxygen that can be carried to the fish in this way is limited by the flow rate and the generally low concentration of oxygen in water. Therefore, most aeration in recirculating systems occurs in the culture tank. The most efficient aeration devices are those that move water into contact with the atmosphere (paddlewheels, propeller-aspirators, vertical-lift pumps). However, these methods usually create too much turbulence within a culture tank to be useful. The most common way to aerate in a recirculating tank system is called diffused aeration. Diffused aeration systems provide low pressure air from a “regenerative” type of blower to some form of diffuser near or on the bottom of a culture tank. These diffusers produce small air bubbles that rise through the water column and transfer oxygen from the bubble to the water.

Studies have determined that diffused aeration systems can transfer oxygen at an average rate of 1.3 kg O_2/kW-h (2.15 lbs./hp - hour) under standard (20º C, O mg/L DO, clean water) test conditions (Colt and Tchobanoglous, 1979). However, these values must be corrected to account for the actual fish culture conditions. To achieve acceptable fish growth rates, the DO concentration should be kept at 5 mg O_2/L or higher. At water temperatures of 28º C, according to Boyd (1982), the diffuser system’s oxygen transfer rate would be only 35 percent of the rate at standard conditions. In this case, the oxygen transfer rate would be reduced to 0.455 kg O_2/kW-h (0.75 lbs./hp - hour). In a well designed recirculating system (one in which solids are removed quickly), the oxygen consumption rate can be estimated as 50 percent of the feed rate (that is, 0.5 kg O_2/kg of feed fed). In a system fed 4.5 kg (10 pounds) of feed over an 18-hour period,the estimated oxygen consumption rate would be approximately 0.125 kg O_2/hour (0.28 pounds/hour). With an actual oxygen transfer efficiency of 0.455 kg O_2/kW-h (0.75 pounds/hp-h), the diffused aeration system would require a blower of approximately 0.275 kw ($^1/_3$ hp) to provide an adequate amount of oxygen. If the fish are going to be fed over a shorter period of time, then peak oxygen demand should be estimated and the blower capacity should be increased.

The density of fish production with aeration alone is usually limited to 30 to 40 kg of fish/m^3 of culture tank volume (0.25 to 0.33 pounds of fish/gal.). In greenhouse systems where algal blooms are common, oxygen is generated during the daylight hours, and culture densities of up to 60 kg of fish/m^3 of culture volume (0.50 pounds of fish/gal.) can be achieved.

Packed column aerators: An ideal location for aerating and degassing water (i.e., removing carbon dioxide) is in the recycle flowstream just before it re-enters the culture tank. As mentioned previously, however, this method does not usually supply enough oxygen. With submerged biological filtration, the concentration of dissolved oxygen will most likely be lowest and carbon dioxide highest at the outflow of this component. Packed column aerators (PCA) are an effective and simple means of aerating water that is already in a flow-stream. A packed column aerator can be identical in design to a trickling nitrifying filter (Fig.11). Water is introduced into a reactor filled with medium. Proper design criteria include non-flooded operation and free air exchange through the reactor. Given a PCA influent DO concentration of 4 mg O_2/L, an effective oxygen transfer rate of 0.75 kg O_2/kw-h (1.25 pounds O_2/hp-h) can be attained. While this is a low transfer rate, the true energy cost for using a PCA in combination with an existing flow-stream is only the energy required to pump water 1.0 to 1.25 meters (3 to 4 feet) to the top of the PCA. If the PCA is to be used for carbon dioxide stripping, a low pressure air blower should be used to force at least five times as much air as water (by volume) up through the PCA medium.

Oxygenation

Pure oxygen is used in recirculating systems when the intensity of production causes the rate of oxygen consumption to exceed the maximum feasible rate of oxygen transfer through aeration. Sources of oxygen gas include compressed oxygen cylinders, liquid oxygen (often referred to as LOX), and on-site oxygen generators. In most applications, the choice is between bulk liquid oxygen and an oxygen generator. The selection of the oxygen source will be a function of the cost of bulk liquid oxygen in your area (usually dependent on your distance from the oxygen production plant) and the reliability of the electrical service needed for generating oxygen on-site.

Adding gaseous oxygen directly into the culture tank through diffusers is not the most efficient way to add pure oxygen gas to water. At best, the efficiency of such systems is less than 40 percent. A number of specialized components have been developed for use in aquaculture applications. For an extensive review of component options, see Boyd and Watten (1989). A review of the more commonly used components follows.

Down-flow bubble contactor: A properly designed low pressure oxygen diffusion system can transfer more than 90 percent of the oxygen injected through the component. One such system is a down-flow bubble contact aerator (DFBC), also referred to as a bicone or a Speece cone. The DFBC system consists of a cone-shaped reactor with a water and oxygen input port at the top (Fig. 14). As the water and oxygen bubbles move down the cone, the flow velocity decreases until it equals the upward velocity of the bubbles. This allows a long contact time between the water and bubbles and nearly 100 percent absorption of the injected gas. The dissolved oxygen concentration of water leaving a DFBC can be as high as 25 mg/L given a system pressure of approximately 1 bar (14.7 PSI).

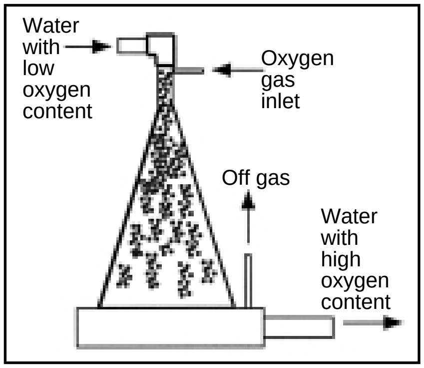

Figure 14. Down-flow bubble contact aerator (after Colt and Watten, 1988).

U-tube diffusers: At high operating pressures, more oxygen can be absorbed by water. A u-tube oxygen diffusion system is an energy efficient method of adding pressure to a flow-stream. A typical u-tube consists of a contact loop, usually a pipe within a pipe (Fig. 15), buried in the ground to at least 10 meters (33 feet), the height of water required to add one atmosphere of pressure (1 bar, 14.7 PSI). The contact loop is placed below tank level to minimize energy requirements, rather than pumping water up hill to gain the extra hydrostatic pressure created by a column of water. Oxygen is mixed with the water at the entrance to the u-tube and travels with the flow to the bottom of the water column. The additional pressure from the water column accelerates the rate of oxygen absorption into the water. The principal advantages of this system are the low energy requirements for oxygenating large flow-streams and the resistance to clogging with particulate solids. The major disadvantage is the construction cost of drilling the shaft and installing the u-tube. Oxygen transfer efficiencies are generally below 70 percent, with effluent oxygen concentrations of up to 250 percent of atmospheric saturation (15 to 20 mg/L).

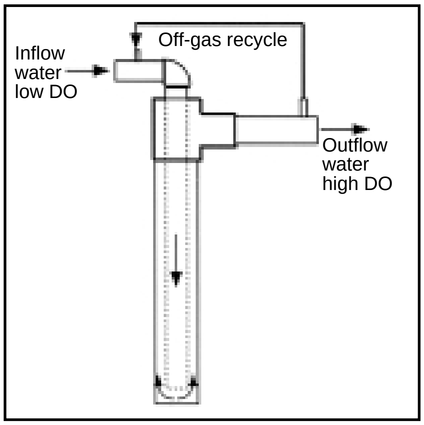

Figure 15. Typical u-tube oxygen diffusion design.

Low head oxygenation system: The multi-staged low head oxygenator (LHO) oxygenates flowing water where there is only a small elevation difference between the source of the water and the culture tank. This situation is often found in raceway systems set up in series. That is, the outflow of one raceway is just slightly (1 to 3 feet) above the inflow of an adjacent raceway. This technology is a patented component (U.S. Patent No. 4,880,445; Water Management Technologies, P.O. Box 66125, Baton Rouge, LA) and is made up of a perforated, horizontal distribution plate and multiple, adjacent, vertical contact chambers (Fig.16). Pure gaseous oxygen enters one (end) contact chamber and oxygen with off-gases (nitrogen and CO_2) exits the adjacent contact chamber.

The oxygen transfer capability of this system is determined by the length of water fall, gas and water flow rates, the DO concentration of the influent water, and the number of contact chambers (Watten 1994). Including packing medium in the contact chambers can improve performance.

Pressurized packed columns: Pressurized packed columns are usually operated in a flooded mode (water fills the reactor). Water enters the top of a pressurized chamber that contains a medium with a high specific surface area (much like packed towers). Oxygen gas is usually intro-

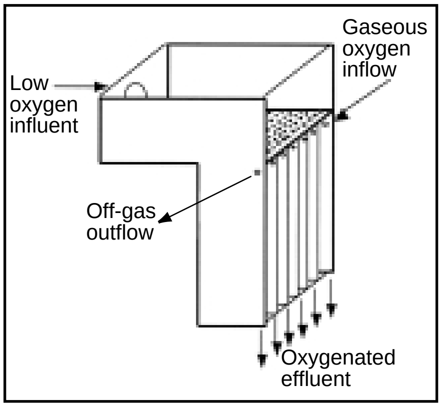

Figure 16. Multi-staged low head oxygenator with front plate removed to show component detail (after Losordo, 1997).

duced at the bottom of the column and travels upward, counter to the water flow. Oxygen transfer efficiency can range from 50 to 90 percent with effluent dissolved oxygen concentrations in excess of 100 mg/L. The major disadvantages of this system are high energy requirements (to provide the pressure) and the buildup of biological growth on the packing medium, which makes periodic cleaning necessary.

Disinfection

Diseases can spread quickly because of the density of fish in recirculating systems. Some chemicals used to treat diseases have a devastating effect on the nitrifying bacteria within the biofilter and culture system. Alternatives to traditional chemical or antibiotic treatments include the continuous disinfection of the recycled water with ozone or ultraviolet irradiation. For more information on disease treatment in recirculating systems, see SRAC publication 452 on the management of recirculating systems.

Ultraviolet irradiation

Microorganisms (including disease-causing bacteria) are killed when exposed to the proper amount of ultraviolet (UV) radiation. Spotte (1979) notes that the effectiveness of UV sterilization depends upon the size of the organism, the amount of UV radiation, and the level of penetration of the radiation into the water. To be effective, microorganisms must come in close proximity to the UV radiation source (0.5 cm, 0.2 inches or less). Turbidity reduces its effectiveness. For a UV radiation system to be effective, the water should be pre-filtered with some form of particulate filtration device.

The most popular and effective type of UV sterilization unit is one with a submerged UV radiation source. In this type of unit, recycled water passes by an elongated UV lamp (much like a neon light bulb). The lamp is inside a quartz glass, watertight jacket and does not come in direct contact with the water. The UV lamp and quartz tube are held within a small diameter pipe through which the treated water flows. As water passes along and around the UV lamp, microorganisms are exposed to the UV radiation. Keeping the quartz jacket clean is imperative to the proper operation of the unit. UV sterilization units are usually rated by their manufacturers according to their water flow rate capacity. Increased efficiency can be achieved by reducing the flow rate through a given unit. The main disadvantage of UV sterilization is the need for clean water with low suspended solids concentrations. Clear water is not always economically achievable in heavily fed recirculating systems. Additionally, the expensive UV lamp must be replaced periodically. The main advantage of UV sterilization is that it is safe to operate and is not harmful to the cultured species.

Ozonation

Ozone (O_3) gas is a strong oxidizing agent in water. Ozone has been used for years to disinfect drinking water. However, because of the high levels of dissolved and suspended organic materials in recirculating systems, the effect of ozone on bacterial populations is questionable (Brazil et al., 1996). The efficiency of the disinfecting action depends upon the contact time and residual concentration of O_3 in the water with the microorganisms. Ozone must be generated on-site because it is unstable and breaks down in 10 to 20 minutes. Ozone is usually generated with either a UV light or a corona electric discharge source. There are many commercial ozone generation units available.

Ozone is usually diffused into the water of a recirculating system in an external contact basin or loop. Water must be retained in this side-stream long enough to ensure that microorganisms are killed and the ozone molecules are destroyed. Residual ozone entering the culture tank can be very toxic to crustaceans and fish. Ozone in the air is also toxic to humans in low concentrations. Great care should be taken in venting excess ozone from the generation, delivery, and contact system to the outside of the building. Ozonation systems should be designed and installed by experienced personnel.

Summary

This publication has outlined the major components and options used in recirculating aquaculture production systems. This is by no means a complete listing, new technologies are continually being developed. One should not attempt to simply link the components discussed here and expect to have a properly operating system. Any system you buy should be the result of years of development, with each component properly sized and integrated for optimal performance. When reviewing your options, always seek the assistance of a knowledgeable, experienced person, one who has designed a currently operating and economically viable recirculating fish production system.

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The Economics of Recirculating Tank Systems:

A Spreadsheet for Individual Analysis

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A well-designed recirculating aquaculture system offers a number of advantages over pond systems. Designed to conserve both land and water resources, recirculating systems can be located in areas not conducive to open pond culture. Operators have a greater degree of control of the fish culture environment and can grow fish year-round under optimal conditions. The crop can be harvested at any time, and inventory can be much more accurately determined than in ponds. This latter characteristic is particularly beneficial when trying to gain financing or insurance for the crop.

Because of these advantages, interest in water recirculating systems for fish production continues to grow, despite the lack of economic information available on their use. This publication and accompanying spreadsheet are designed to help prospective recirculating system operators examine the economics of proposed systems. With modifications to the example spreadsheet, the same format can be used to monitor costs and returns once systems are operating. The Excel spreadsheet can be downloaded from the following Internet address: http://www.agr.state.nc.us/aquacult/rass.html.

The spreadsheet in this publication uses tilapia for the example species. However, the resulting figures on costs and returns are not meant to be used as an economic analysis of tilapia production. Each individual using the spreadsheet should input equipment and supply costs and the appropriate market price for the specific system being analyzed.

System design

There is no single recommended design for growing fish in a recirculating aquaculture system (RAS). In general, a system includes tanks to culture fish, pumps to maintain water flow, and some form of water treatment to maintain water quality. Following are a few general considerations on system design and how design can affect profitability. For a more complete explanation of component options and management issues see SRAC publications 450, 451 and 452.

Proper sizing of all system components is very important. If equipment is oversized for the application, the system will function but will be very costly. If equipment is undersized, the system will not be able to maintain the proper environment to sustain fish production.

Operators should size equipment according to the maximum daily amount of feed placed into the system. The estimated daily feed rate is based on the system carrying capacity, which does not usually exceed 1 pound of fish per gallon of water for even the most efficient system. Once carrying capacity and feed rate are defined, the operator estimates the size of equipment components by calculating the required flow rate. The flow rate of each component must be sufficient to flush out and treat any wasted feed and by-products of fish metabolism, while supplying a uniform concentration of oxygen.

Because equipment is sized to maximum feeding rates, the most inefficient stock management method is to stock fingerlings at low densities in a tank and grow them to market size within the same tank. Most RAS operators try to make maximum use of each

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tank's carrying capacity by stocking fish at increasingly lower numbers as the fish grow in size. The more efficient the use of system carrying capacity, the more fish can be moved through the system annually, which generally lowers the cost per pound harvested. The trade-off is that the more often fish are restocked, the higher the labor cost and greater the chance of mortality if fish become stressed from the move.

Operators also face a trade-off when determining both the size of tanks and the configuration of equipment for filtering and oxygenating water. The use of fewer, larger tanks, or several tanks sharing water treatment equipment, is usually much less expensive than having a number of smaller tanks that do not share water or components. Managing quality and disease prevention, however, is typically more effective where water is not shared between tanks. There is less risk of losing large portions of the fish crop when each tank has its own set of treatment equipment.

There are economies of scale for individual tank size and for the size of the entire system. Up to a point, the increase in system size generally results in a lower cost per pound produced, because the fixed costs associated with the building and equipment can be spread over more pounds harvested.

The example system

The data used for this publication are taken from experiences in a small unit at the North Carolina State University Fish Barn Project (NC Fish Barn).

The NC Fish Barn system grows fish in nursery tanks, then grades and splits the population into larger growout tanks as the fish gain weight. The system consists of six tanks: one 1,500-gallon (5.68-cubic meter) quarantine tank (Q); a 4,000-gallon (15.14-cubic meter) nursery tank (N), and four 15,000-gallon (56.78-cubic meter) growout tanks (G1, G2, G3 and G4). The quarantine and nursery tanks have their own water filtration systems, while each pair of growout tanks shares a water treatment system. A more detailed description of the system and equipment can be found in Hobbs et al., 1997.

Fish are initially stocked in the Q tank, screened for diseases for 35 days, then harvested and restocked into the N tank. After 35 days, the fish are transferred to one of the four G tanks where they remain an additional 140 days until harvest. This 140-day period is broken down into four distinct production units of 35 days each (defined as g1, g2, g3 and g4 in the spreadsheet). Each of these units has a different feed rate, oxygen demand, and pumping need. (An alternative to this configuration would be to move the fish into a different tank for each of the 35-day periods).

Once the system is fully stocked, one of the four G tanks is harvested for sale every 35 days. The system has a maximum culture density of 0.8 pounds of fish per gallon of water (103 kgs of fish per cubic meter of water) in each growout tank, and each harvest yields approximately 12,400 pounds (5,636 kgs) of fish. With 10.43 harvests annually (one every 35 days once the facility is fully stocked), total production for the facility is approximately 130,000 pounds (59,091 kgs) per year.

Using the spreadsheet

The Recirculating Aquaculture System Spreadsheet (RASS) must be supplied with accurate and realistic input data based on a properly designed system. Proper design means that the equipment components work together to produce the amount of fish in the time period stated.

The spreadsheet is divided into five sections. The user supplies information for the first three sections. Data in the final two sections are calculated from this information. Shaded areas in the tables indicate needed information and are represented as bold type in the spreadsheet. "Spreadsheet Cell Range" and cell numbers refer to the location of information within the Excel spreadsheet.

Section 1: Specify the Initial Investment Spreadsheet Cell Range B13:E25

The initial investment cost is supplied by the user in cells E16:E20. The total is calculated in cell E21. The investment includes the total value of purchased land, a settling pond, building, equipment, and construction labor, as well as the current value of any owned assets used in the business.

Annual depreciation on building and equipment (E22) is the amount of money that must be earned each year by the business to eventually replace equipment when it wears out.

Interest rate on operating capital (E24) is used to calculate a cost of interest on variable inputs (oxygen, energy, bicarbonate, fingerlings, chemicals, maintenance and labor). The interest charge could be interest owed to a bank for the financing of the purchase of these inputs, or the charge could be for the cost of using the owner's own funds to purchase variable inputs. A cost of using owner's funds is used because the investment of funds in the recirculating system means that the owner foregoes potential earnings from an alternative investment.

Interest rate on building and equipment (E25) is used to calculate an annual interest charge based on the average investment. Again, this could be interest owed on a bank loan used to finance the initial investment, or it can represent earnings that could have been made on an alternative investment.

Section 1.
Specify the Initial Investment
Spreadsheet Cell Range = B13:E25

Initial investment	
land	$8,000
settling pond	$5,000
equipment	$172,500
building	$60,000
construction labor & overhead	$30,000
Total initial investment	$275,000
Annual depreciation on building and equipment	$19,100
Interest rate on operating capital	9%
Interest rate on building and equipment	11%

Section 2: Specify the Cost of Inputs, Sale Price, and System Parameters
Spreadsheet Cell Range = B27:E54

Variable costs

Variable costs are those directly related to production. In the cell range E31:E38 the user specifies the cost per unit of oxygen, energy, bicarbonate, fingerlings, chemicals, maintenance and labor. The quantity used of each of these inputs is defined in Section 3.

Fixed costs

Fixed costs are incurred regardless of whether or not production occurs. They are *Liquid oxygen tank rental* (E41), *Electrical demand charge* (E42), and *Building overhead* (E43). Each of these is specified as a cost per month.

Sale price

Average overall sale price (E45) is the weighted average sale price per pound, taking into account the size distribution at harvest and differing prices for various sizes of fish. The example uses $1.25 so that the system will break even (with $0 profit and $0 losses).

System parameters

The remainder of this section (E48..E54) contains system parameters that will be needed for calculations related to costs and returns. *Annual production* (E48), *Average size at harvest* (E49), and the *Survival rate* (specified in the next section) are used to calculate the initial stocking density.

There are six production units in this example (*Number of production units* [E50] = 6). As discussed above, a production unit refers to a specific tank or life stage of the fish. Here, three tanks are used: a Q tank, an N tank and a G tank. Fish remain in the Q tank and N tank for 35 days each. Within the

Section 2.
Specify the Cost of Inputs, Sale Price, and System Parameters
Spreadsheet Cell Range = B27:E54

	unit or description	cost or amount
Variable Costs:		
Liquid oxygen	$/100 cu. ft.	$0.30
Energy	$/kwh	$0.065
Bicarbonate	$/lb.	$0.190
Fingerlings	$/fingerling	$0.090
Chemicals	$/cycle	$100.00
Maintenance	$/month	$637.00
Labor: management	$/month	$2,000.00
Labor: transfer & harvest	$/hour	$6.50
Fixed Costs:		
Liquid oxygen tank rental	$/month	$250.00
Electrical demand charge	$/month	$100.00
Building Overhead	$/month	$100.00
Average overall sale price	$/lb.	$1.25
System Parameters		
Annual production	lb.	129,107
Average size at harvest	lb.	1.25
Number of production units	number	6
Days per production unit	days	35
Kwh per lb. of production	kwh/lb. of prod.	2.30
System volts	volts	230
Transfer/harvest labor	hrs. per cycle	64

G tank, the fish go through four 35-day stages. Note that the *Days per production unit* (E51) must be the same for each unit in order for the spreadsheet to accurately calculate costs and returns in Section 5.

The *Kwh per lb. of production* (E52) is used to calculate energy costs for the total system and each production unit. This variable is calculated by adding up the total KW usage of the system—including energy usage for pumps, blowers and other equipment as well as heating, ventilation and air-conditioning—converting this to kwh used per year, and then dividing by the number of pounds produced. (For the example, the total energy demand is 34 KW. Multiply by 24 hours per day and 365 days per year, then divide by annual production of 129,107 pounds to arrive at 2.30 kwh per pound of production).

System volts (E53) is used to calculate required amperage in Section 5. This is a useful number for planning energy requirements for the facility.

Transfer/harvest labor (E54) is the number of hours of labor required per cycle in addition to *Labor: management* (defined in E37).

Section 3: Specify Operating Parameters per Production Unit

Spreadsheet Cell Range B56:J64

Each column in this section represents a production unit, which could be a tank or group of tanks managed in the same manner, or it could refer to a particular life stage. For example, two tanks stocked at the same time with the intent to transfer and harvest fish at the same time, and in which fish are fed and managed in the same manner, could be treated as one production unit. Or, as in the table below and spreadsheet example, two of the six columns (Q & N) refer to particular tanks, while the remaining four (g1, g2, g3, g4) refer to a production stage for fish that remain within the same tank.

Section 3.
Specify Operating Parameters per Production Unit
Spreadsheet Cell Range = B56..J64

			Growout tank			
	Q tank	N tank	g1	g2	g3	g4
Water volume, gallons	1,500	4,000	15,000	15,000	15,000	15,000
Size stocked (grams)	1	15	60	135	250	385
Size harvested (grams)	15	60	135	250	385	567
Survival rate	85%	99%	99%	99%	99%	99%
Feed cost, per pound	$0.52	$0.38	$0.21	$0.21	$0.21	$0.21
Feed conversion	1	1.1	1.3	1.6	1.6	1.6

Water volume, gallons (E59:J69) is used to calculate the *Maximum standing biomass, lbs. per gal. of water* (E73:I73) for any one tank, discussed in Section 4.

Size stocked (E60:J60) is the average size of fish stocked into that production unit. *Size harvested* (E61:J61) is their average size when transferred or harvested from the system. In the example, fish are initially stocked at 1 gram into the Q tank, and transferred into the N tank when they reach 15 grams.

Survival rate (E62:J62) is the percentage of survival for that production unit. In the example, the lower survival rate for the Q tank includes the discarding of runts when the fish are graded before restocking into the N tank.

Feed cost, per lb. (E63:J63) is the average cost per pound for feed fed to that production unit. *Feed cost, per lb.* and *Feed conversion* (E64:E64) are used to calculate the cost of feed for each production unit, for each cycle, and annually. Feed usage is also used to calculate the amount of energy used, as discussed in the following section.

Spreadsheet calculation of costs and returns

Section 4: Use of Primary Inputs and Costs per Production Unit

Spreadsheet Cell Range B66:J87

This section summarizes the quantity and cost of primary operating inputs—fingerlings, feed, energy, oxygen, and bicarbonate—used over one cycle, and extrapolates this information to an annual basis. No user input is required in this section.

In the example, once the fish culture system is fully stocked after 210 days, the system will have 10.43 harvests per year (365 days/ 35 days). Thus, each number in the *Cycle Total* (column L) is multiplied by 10.43 to calculate the *Annual Total* (column M).

Beginning number of fish (E69:J69) begins with the original stocking density and adjusts that number according to the *Survival rate* (E62:J62).

Ending number of fish (E70:J70) is based on density and survival for each production unit.

Beginning biomass, lbs. of fish (E71:J71) is based on the number of fish and average weight stocked into that production unit.

Ending biomass, lbs. of fish (E72:J72) is based on the number of fish and weight transferred or harvested from that unit.

Maximum standing biomass, lb. per gal. of water (E73:J73) gives the pounds of fish per gallon of tank water at the end of that production period.

Feed used (E74:J74) is calculated from the specified *Feed conversion ratio* (E63:J63) and the difference between the *Beginning biomass* (E71:J71) and *Ending biomass* (E72:J72).

The *Kwh used* is calculated for each production unit as a weighted percentage of the feed usage for that unit multiplied by the total amount of kwh used for the cycle. The total kwh for the cycle is based on estimated energy usage of 2.30 kwh per pound of production. For example, one cycle yielding 12,354 pounds (5,615 kg) of fish requires an estimated 28,414 kwh of energy. The g1 production unit consumes 11.72% of feed used during the cycle (2,172 pounds feed/18,524 pounds feed), so the estimated energy use during that 35-day unit is 3,330 kwh (11.72% x 28,414), given in cell G75. The cost of energy for that period, given in G82 as $217, is calculated using the user-specified cost of $0.065 per kwh (E45).

Oxygen used, cubic feet (E76:J76) is calculated as follows: pounds of feed (E74:J74) x 30% (the amount of oxygen used per pound of feed, this is system specific) x 12.05 (a conversion factor).

Bicarbonate used (E77:J77) allows for 0.175 pound of sodium bicarbonate used per pound of feed fed.

Costs by production unit (E80:J87) are calculated using the cost per input specified in Section 2.

Section 5: Summary of Annual Costs and Returns to System in Full Production

Spreadsheet Cell Range = B89:J122

This section summarizes the costs and returns per cycle and annually for this system once it is in full production (after 210 days). Net returns are calculated before tax.

Days per production unit (D91) repeats information given in cell E51.

The Number of cycles per year (D92) is simply 365 days divided by *Days per production unit*.

Required system amps (D93) is calculated from *System volts* (E53) and kwh usage assuming a power factor of one.

Overall survival (F91) is calculated using survival given in E62:J62, and *Cycle FCR* (F92) from feed conversion ratios in E64:J64.

The cell range C96:J122 calculates system costs per cycle, annually, and per pound based on information specified previously in the spreadsheet.

Section 4.
Use of Primary Inputs and Costs per Production Unit

Spreadsheet Cell Range = B66:J87

			Growout tank				Cycle	Yearly
Inventory & Input Use:	Q tank	N tank	g1	g2	g3	g4	total	total
Beginning number of fish	12,252	10,415	10,310	10,207	10,105	10,004	12,252	127,775
Ending number of fish	10,415	10,310	10,207	10,105	10,004	9,904	9,904	103,286
Beginning biomass (lbs. of fish)	27	344	1,361	3,032	5,558	8,474	27	281
Ending biomass (lbs. of fish)	344	1,361	3,032	5,558	8,474	12,354	12,354	128,838
Max. standing biomass (lbs./gal.)	0.23	0.34	0.20	0.37	0.56	0.82	--	--
Feed used, lbs.	317	1,119	2,172	4,042	4,665	6,209	18,524	193,179
Kwh used	486	1,717	3,331	6,200	7,156	9,525	28,415	296,328
Oxygen used, cubic ft.	1,145	4,045	7,851	14,612	18,864	22,447	66,964	698,342
Bicarbonate used, lbs.	55	196	380	707	816	1,087	3,242	33,806
Costs:								
Fingerlings	$1,103						$1,103	$11,500
Feed	$165	$425	$456	$849	$980	$1,304	$4,178	$43,575
Energy	$32	$112	$217	$403	$465	$619	$1,847	$19,261
Oxygen	$3	$12	$24	$44	$51	$67	$201	$2,095
Bicarbonate	$11	$37	$72	$134	$155	$206	$616	$6,423
Total of above costs for this unit	$1,313	$586	$768	$1,430	$1,651	$2,197	$7,945	$82,855
Cumulative cost for cycle	$1,313	$1,899	$2,667	$4,098	$5,748	$7,945	$7,945	$82,855
Cumulative cost per lb.	$3.82	$1.40	$0.88	$0.74	$0.68	$0.64	$0.64	$0.64

Section 5.

Summary of Annual Costs and Returns to System in Full Production

Spreadsheet Cell Range = B89:J122

Days per production unit	35	Overall survival	81%
Average number of cycles/yr.	10.43	Cycle FCR	1.5
Req. system amps	147		

	unit	cost/unit	quantity/ cycle	$/cycle	$/year	$/per lb. of fish	% of total
Gross Receipts	lb.	$1.25	12,354	$15,443	$161,048	$1.25	
Variable Cost							
fingerlings	unit	$0.09	12,252	$1,103	$11,500	$0.09	7%
feed	lb.	$0.23	18,524	$4,178	$43,575	$0.34	27%
energy	kwh	$0.07	28,415	$1,847	$19,261	$0.15	12%
oxygen	100 cubic feet	$0.30	670	$201	$2,095	$0.02	1%
bicarbonate	lb.	$0.19	3,242	$616	$6,423	$0.05	4%
chemicals	$ per cycle	$115.07	1	$115	$1,200	$0.01	1%
maintenance	$ per cycle	$732.99	1	$733	$7,644	$0.06	5%
labor: management	$ per cycle	$2,301.37	1	$2,301	$24,000	$0.19	15%
labor: transfer & harvest	hour	$6.50	64	$416	$4,338	$0.03	3%
interest on variable costs	dol.	9%	6,307	$327	$3,406	$0.03	2%
Subtotal, Variable Cost				$11,837	$123,442	$0.96	77%
Fixed Cost							
Oxygen tank rental	dol.			$288	$3,000	$0.02	2%
Electrical demand charge	dol.			$115	$1,200	$0.01	1%
Building overhead	dol.			$173	$1,800	$0.01	1%
Interest on initial investment	dol.			$1,226	$12,788	$0.10	8%
Depr. on bldg. & equip.	dol.			$1,832	$19,100	$0.15	12%
Subtotal, Fixed Cost				$3,633	$37,888	$0.29	23%
Total Cost				$15,470	$161,330	$1.25	100%
Net Returns above Var. Cost				$3,606	$37,606	$0.29	
Net Returns above Total Cost				-$27	-$282	$0.00	

Interpreting the spreadsheet results

This publication is not an evaluation of the economics of tilapia production. A sale price of $1.25 was chosen so that the example system would have annual costs nearly equal to annual returns.

It is important to keep in mind that before the end of the first cycle on day 210, costs are incurred while no fish are harvested and sold. Until that time, the cost of operations must either be paid by additional owner funds or bank financing. To approximately calculate the point at which the system becomes self-supporting (can pay all fixed and variable costs), divide the total costs per cycle by the net returns per cycle. For example, if the sale price were $1.65 per pound, Total Costs per Cycle would be $15,470 and Returns above Total Costs would be $4,957. This is equal to 3.1 cycles ($15,470/$4,957) or 651 days (3.1 cycles x 210 days per cycle). The system would not become self-supporting until approximately 2 years from startup.

This spreadsheet can be used to test the effect on costs and returns of changes in sale price, feed conversion, survival, or the cost of energy and other inputs. Users can also examine the change in profitability based on a change in the stocking and transfer of fish or overall size of the system. For example, more frequent moves of fish between tanks could make better use of tank carrying capacity, increasing the amount of fish that could be harvested annually. Or, a more energy intensive system might support a higher carrying capacity per tank. Either of these may result in increased profit if the costs associated with each (higher labor cost, stress that may result in lower survival in the case of more frequent moves, and a higher energy cost if the system were reconfigured) do not outweigh the increase in production. Larger systems—more tanks and larger tanks—also often increase the profitability of recirculating systems.

Caveats (a warning)

There is no single recommended design for recirculating aquaculture systems. Therefore, it is impossible to supply a ready-made cost/returns spreadsheet that will be suitable for every system. Operators with existing or proposed systems similar to the example presented here can use this spreadsheet. Radically different systems may require extensive modifications of the spreadsheet structure by the user. The example spreadsheet is simple in design and does not contain any macro-programming. It can be modified once cells are unprotected. When working with the original spreadsheet or a modified version, keep in mind that it can only evaluate the economics of a properly designed system, and can not correct for flaws in design.

References

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For additional suggested reading, see the Internet site.

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