Water Quality Requirements and Environmental Impacts of Recirculating Aquaculture Systems

Thomas M. Losordo¹, Ronald F. Malone², and Shulin Chen²
¹North Carolina State University, Raleigh, North Carolina
²Louisiana State University, Baton Rouge, Louisiana

I. INTRODUCTION

Recirculating aquaculture systems have been the focus of scientific and commercial research and development for decades. Primary interest in these types of systems has grown out of limitations on water supplies, suitable land for traditional aquaculture ponds and a growing concern for the environmental impact of effluents from traditional production systems. This paper discusses the rationale for using recirculating production technology, outlines the pertinent water quality issues, discusses the technological options for water reuse, characterizes the wastes generated by recirculating systems and discusses their environmental impacts.

Water Quantity Limitations

Traditional aquaculture production in ponds utilizes large quantities of water. Approximately 9.4 million liters of water per hectare is required to fill a pond and an equivalent volume is required to make up for evaporation and seepage during the year. Assuming an annual pond yield of 5600 kilograms (kg) per hectare (ha) per year (y), approximately 838 liters of makeup water are required per kg of production. Tucker and Robinson (1990) set 140 liters/minute/hectare as the absolute minimum water supply requirement for catfish farming in ponds in the southern US. Water exchange rates in excess of 80% of the total pond volume per day have been reported for intensive marine shrimp production in ponds (Wyan and Sweeney, 1991). In these very intensive production systems water usage per kilogram of production can be as high as 67,000 liters. In many areas of the United States, aquaculture is not possible in ponds because of limited water supplies or an absence of suitable land for pond construction.

The rate of water exchange required to maintain good water quality in tanks is very high. Ray (1979) recommends that at maximum carrying capacity, a raceway system for the intensive production of catfish (Ictalurus punctatus) should receive a flow of 0.25 liters/min. per kg of biomass. Noting that the yearly production is approximately 3 - 4 times the carrying capacity, the water usage per kg of annual production can be estimated to be between 32,000 and 66,000 liters. These water requirements have limited this type of production practice and will preclude expansion of existing industries based upon flow-through tank based technology.

Aquaculture Effluent Issues

Concern for the environment has led to regulation of the outfalls of aquaculture production facilities within the US. Cold water production facilities discharging more than 30 days per year, producing more than 9090 kg of product and feeding more than 2272 kg of feed must hold a National Pollution Discharge Elimination Permit (NPDES). Similarly, a warm water production facility that discharges more than 30 days per year and produces more than 45,454 kg of harvestable per year must hold an NPDES permit and comply with water quality regulations. As the US aquaculture industry grows, the monitoring and control of effluent flow-streams will become more important to the regulatory agencies (Brune, 1991) and could potentially limit the growth of the industry in many areas. This could force the aquaculture industry to develop or adapt production systems that will have less environmental impacts due to reduced waste discharge or effluents that are more easily controlled or treated.

II. SOURCE WATER QUALITY AND QUANTITY

In general terms, water that is suitable for most traditional marine and fresh water aquaculture production practices would be suitable for recirculating aquaculture technology. The water supply should be free of pathogenic organisms, industrial, domestic or agricultural wastes, and wild aquatic organisms (e.g. fish, insects). Also of primary importance is the chemical makeup of the water. The water supply should not contain high levels of ammonia-nitrogen, nitrite-nitrogen and to a lesser extent nitrate-nitrogen. The concentration of each of these parameters should fall within the range of concentrations set for culture tanks (Table 1). The pH of the water should be between 6.5 and 8.5 and a high (> 50 mg/l as CaCO₃) alkalinity is preferable. Dissolved oxygen content is not of critical concern although high levels (>110 % saturation) of dissolved nitrogen and carbon dioxide should be minimized. Source water temperatures are not critical for recirculating systems with high hydraulic retention times.

The quantity of source water required by a recirculating system will depend largely upon the system configuration. In systems utilizing some form of denitrification process, the quantity of source water required is limited to water lost during the system cleaning operations. In the United States, denitrification has not been widely used and the quantity of source water used is usually controlled by the type of recycled water treatment process that is employed. The most water intensive recirculating systems are those utilizing drum or disk screen filter components for non-settleable solids removal. Screen filter technology utilizes some form of fine mesh material through which a flow-stream passes with the non-settleable solids being retained on the screen. A common method of removing solids involves rotating the screen surface past high pressure spray jets of water. The solids are carried away from the screen in a small flow-stream. This wastewater stream is usually 1% of the total recycle stream flowing through the screen filter. The new water requirements for these systems will be dictated by the water used in cleaning the screen.

In recirculating systems that utilize very little water for filter maintenance, new water additions are used to control the nitrate-nitrogen concentrations. In these systems the flow-rate of new water is a function of the rate of nitrate production within the system and an acceptable nitrate concentration within the tank. Although it is possible to estimate the required source water by performing a mass balance for nitrate nitrogen on the system, this approach almost always over-estimate the required flow (Losordo, 1991). Passive microbial denitrification processes are usually ongoing within recirculating production system components (Bovendeur et al. 1987). Significant amounts of nitrate-nitrogen are converted to nitrogen gas, and unless this nitrate "sink" is accounted for, the mass balance calculation may over-estimate the required flow by more than 50%.

In general, recirculating systems in the United States replace between 2 to 10% of the total system volume per day. Losordo and Westemann (1992) describe a prototype recirculating system being developed at North Carolina State University for the production of finfish. The authors estimated that, based upon the growth trials with a 4 tank system, a 43,500 kg per year tilapia production facility would consist of eight (8) 22,700 liter grow-out systems and a nursery system of similar volume (a total production system volume of 204,300 liters). Given the 2 to 10% water replacement estimates, the production system's source-water usage per kg of fish can be estimated at between 34 and 171 liters. Figure 1 compares water usage for the NCSU system utilizing a 6% new water volume exchange rate with that of the traditional pond and flow-through tank production systems described previously.

III. CRITICAL SYSTEM WATER QUALITY PARAMETERS

The economic viability of producing aquatic crops in recirculating systems is largely dependent on maintaining non-stressful conditions within the culture system. Critical water quality parameters controlling stress include the concentrations of dissolved oxygen, unionized ammonia-nitrogen, nitrite-nitrogen, pH, alkalinity and carbon dioxide. Producing fish in a cost effective
manner requires that these water quality variables be controlled during periods of rapid fish growth. To provide for rapid growth, fish must be fed appropriately large quantities of a high protein pelleted diet.

Growth reductions and increased incidence of disease can result from stress due to poor water quality. The required level of water quality of the culture tank varies according to the species. However, some general guidelines can be assumed and have been listed in Table 1.

Feeding rate, feed composition, fish metabolic rate and quantity of wasted feed detrimentally impact culture tank water quality. As feeds are introduced into the culture system, they are either consumed by the fish or left to decompose in the system. The by-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. Recirculating systems must be designed and operated to effectively remove waste and metabolites from the system to maintain an optimum culture environment.

IV. UNIT PROCESSES AND WATER QUALITY MAINTENANCE

A key to successful recirculating production systems is the use of a cost effective water treatment system. All recirculating production systems utilize processes to remove waste solids, oxidize ammonia and nitrite-nitrogen, and aerate and/or oxygenate the water (see Figure 2). The following is a brief description of the water treatment processes that must be addressed when utilizing recirculating aquaculture technology.

Waste Solids

Pelleted feeds used in aquaculture production consist of protein, carbohydrates, fat, ash and moisture. The portion not assimilated by the fish is excreted as a highly organic waste (fecal solids). The fecal solids along with uneaten feed will consume dissolved oxygen and generate ammonia-nitrogen when broken down by bacteria within the system. For this reason waste solids should be removed from the system as quickly as possible. Waste solids can be classified into suspended and dissolved solids. Suspended solids can be further classified into settleable and non-settleable solids.

Settleable Solids Control: Settleable solids are generally the easiest to deal with and should be removed from the water in the tank as rapidly as possible. Settleable solids are large solids (> 100 microns) that will settle out of the water within one hour under still conditions. Settleable solids can be removed within round culture tanks, where they accumulate on the bottom in the center, or they can be kept in suspension with continuous agitation and removed with a properly designed sedimentation tank (clarifier). The sedimentation process can be enhanced through the addition of steeply incline tubes (tube settlers) within the sedimentation tank to reduce flow turbulence and promote uniform flow distribution.

Non-settleable Solids Control: From a fish producers point of view, the difference between non-settleable solids and settleable solids is a practical one. Non-settleable solids (< 100 microns) will not settle out of the water column under still conditions within one hour and would not be expected to be removed by conventional settling. Non-settleable solids are not always dealt with adequately in a recirculating production systems. If not removed, non-settleable solids can significantly limit the amount of fish that can be grown in the system and can interfere with and irritate the gills of fish. The most popular treatment method for removing non-settleable solids generally involves some form of mechanical filtration. The two types of mechanical filtration most commonly used are screen filtration or granular media filtration (sand or pelleted media).
Fine Suspended and Dissolved Solids Control: Fine non-settleable solids (< 30 microns) can accumulate in a recirculating system. At times, 50% of the total suspended solids found in the system will fall in this difficult size category. These solids increase the oxygen demand of the system and have been shown to cause gill irritation and damage in finfish (Chapman et al., 1987). Additionally, dissolved organic solids (protein) can contribute significantly to the oxygen demand of the total system.

Fine non-settleable solids and dissolved solids cannot be easily removed by sedimentation or mechanical filtration technology. Foam fractionation (also referred to as protein skimming) has been employed to remove these solids from recirculating tank systems (Heguenin and Colt, 1989; Timmons et al., 1991). Foam fractionation, as employed in aquaculture, is described as a general process of introducing air bubbles at the bottom of a closed column of water that creates foam at the air/water interface. As the bubbles rise through the water column, solid particles attach to the bubbles surface forming the foam at the top of the column. The foam build-up is then channeled 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 (Chen et al., 1989). Although the efficiency of foam fractionation is subject to the chemical properties of the water, the process can generally be used to significantly reduce water turbidity and oxygen demand of the culture system.

Nitrogen Considerations

Total ammonia-nitrogen (TAN), consisting of un-ionized ammonia (NH₃) and ionized ammonia (NH₄⁺), 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 9.0 the 50% is in the un-ionized form. While the lethal concentration of ammonia-nitrogen for many species has been established, the sublethal effects of ammonia-nitrogen have not been well defined. Growth reduction may be the most important sublethal effect (Mead 1985). Colt and Armstrong (1981) suggest that growth is significantly reduced at un-ionized ammonia concentrations of 0.05 - 0.2 mg/L for most aquatic animals.

Nitrite-nitrogen (NO₂⁻) 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. 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 removed from the tank. Concentrations of nitrite-nitrogen should not exceed 0.5 mg/L for long periods of time. Fortunately, Nitrobacter bacteria which are also present in most biological filters utilize nitrite-nitrogen as an energy source and produce nitrate as a by-product.

Nitrites are not generally of great concern to the aquaculturist. Studies have shown that aquatic species can tolerate extremely high levels (> 100 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 removed through denitrification processes that occur within components of the production system (e.g. settling tank, filter reactor).
Nitrogen Control

Control of the concentration of un-ionized ammonia-nitrogen (NH₃) in the culture tank is a primary objective of recirculating treatment system design. Ammonia-nitrogen must be converted to a less toxic form or 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 including air stripping, ion exchange, and biological filtration, biological filtration is the most widely used. In biological filtration (also referred to as biofiltration), a media with a large surface area is provided for nitrifying bacteria attachment and growth. As noted in the previous section, 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, and plastic plates are commonly used biofiltration substrates. The configuration of the substrate and the manner in which it comes into contact with wastewater defines the water treatment characteristics of the biological filtration unit. Common configurations for biological filters include rotating biological contactors (RBC), packed bed filters and expandable media filters.

pH and Alkalinity

pH is a measure of the hydrogen ion (H⁺) concentration in water and indicates the degree to which water is either acidic or basic. The pH of water affects the state of many other water quality parameters and the rates of many biological and chemical processes. As such, 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 (HCO₃⁻) and carbonate (CO₃⁻) are the predominant bases or source of alkalinity in most waters. Waters with high alkalinity tend to be more strongly buffered against pH change than those of low alkalinity.

Nitrification is an acid producing process. As ammonia-nitrogen is transformed to nitrate-nitrogen by nitrifying bacteria, hydrogen ions are produced. The hydrogen ions combine with bases such as hydroxide (OH⁻), carbonate and bicarbonate reducing alkalinity and the pH. pH levels below 4.5 are dangerous to fish and 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 (NaHCO₃).

Dissolved Gases

Although ammonia-nitrogen buildup is a primary factor limiting a recirculating system's carrying capacity, maintaining adequate dissolved oxygen (DO) concentrations in the culture tank and filter system is also of critical importance. To maintain adequate DO levels in the culture tank, oxygen must be input to the tank at a rate equal to 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. Colt et al. (1991) indicate that approximately 1 kg of oxygen addition is required per kg of feed added.

Carbon dioxide (CO₂) 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 greatly toxic to fish when sufficient dissolved oxygen is present (Boyd, 1982). 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 (Colt and Tchobanoglous, 1981).
The buildup of dissolved nitrogen gas is rarely a problem in warm water aquaculture systems. However, caution is advised when pressurized aeration or oxygenation systems are employed, as atmospheric nitrogen can become supersaturated in water if it is entrained into the pressurized flow stream. Aquatic organisms subjected to elevated concentrations of dissolved nitrogen gas can develop problems with "gas bubbles" within their circulatory systems and die.

Dissolved Gas Management

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 crop in one half hour or less.

Aeration and Degassing: The addition of atmospheric oxygen into 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 due to the fact that 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 location 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 utilizing submerged biological filtration, the concentration of dissolved oxygen will most likely be lowest and carbon dioxide levels will be highest. Packed column aerators (PCA’s) 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 media. A perforated plate or spray nozzle is used to evenly distribute the incoming water over the media. The packed column is operated under non-flooded condition such 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 media.

Pure Oxygen Injection: In intensive production systems, the oxygen consumption rate of fish and bacteria may exceed the rate 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 warmwater applications (> 20° 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 oxygen 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 are capable of oxygen absorption efficiency in excess of 90%. However, as with tank aeration (with air), the culture tank is not the optimum location for oxygen diffusion with common "air stone" diffusers. Because of the short contact time of bubbles rising through a shallow (< 2 m) water column in tanks, air stones diffusers have oxygen absorption efficiencies not greater than 40%. 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, or a down-flow bubble contactor.
V. WASTEWATER CHARACTERISTICS

Like other aquaculture production systems, recirculating systems generate wastes. The characteristics and subsequent environmental impacts of the wastes are important factors affecting the application, evaluation and siting of recirculating systems. The wastes generated by recirculating systems are in two forms: particulate and dissolved. The majority of the biochemical oxygen demand (BOD₅) and inorganic and organic nutrients in the waste stream are carried in the particulate form, usually measured as total suspended solids (TSS) (Chen et al., 1991). For this reason, the TSS produced and discharged by a recirculating system will largely determine the extent of environmental impact of the system.

Waste Excretion

Wastes generated from a recirculating system originate from fish feed. On a dry weight basis, only a small portion of the feed input is actually assimilated and converted to fish tissue. Given a typical feed conversion ratio 1.5 to 2 and a moisture content of the feed at 10% and the fish at 75% (Hopkins and Manci, 1989), approximately 81-86% of the feed will be excreted as fecal matter, expended to support physiological functions, or wasted as uneaten feed. Although the waste generated in aquacultural operations may also include substances such as therapeutic drugs, chemicals, and other additives to fish feed, the BOD₅, TSS, and nutrients, mainly nitrogen (N) and phosphorus (P) are the main concern. Wimberly (1990) determined that 23% of the BOD₅ excreted by catfish in a recirculating system was in soluble form with the major portion (77%) in the particulate form.

Total suspended solids production has been estimated through excretion studies. Fish excretion studies for several culture species have indicated that the direct TSS excretion rate for trout is 0.40 to 0.52 kg TSS / kg feed (Speece, 1973; Liao and Mayo, 1974) and 0.43 kg TSS / kg feed for catfish (Wimberly, 1990). Other reported TSS excretion rate for catfish ranged from 0.18 to 0.69 kg TSS / kg feed (Page and Andrews, 1973; Gordon, 1974; Ruane et al., 1977). Waste nitrogen (N) results from the degradation of protein, a main component in fish feed. Given that typical commercial fish diets contain up to 30 to 50 % protein (Downey, 1981), the total nitrogen in fish feed can be estimated as 4.8 to 8 % as dry weight. Iwama (1991) indicates that 67 to 75% of the N in feed for salmonids is lost to the environment as Total Kjeldahl Nitrogen (TKN). We can thus estimate that the discharge of TKN from an aquacultural system will be approximately 3.2 to 6.0 % of the feeding rate.

Phosphorus (P) excretion can also be estimated by a mass balance on feed utilization and waste generation. The estimated content of P in prepared diets for salmonid, tilapia and carp range from 0.93 to 3.06 % by weight (Ketola, 1982; Penczak et al., 1982; Beveridge, 1984). If approximately 19 % of the P is retained in fish (Ketola, 1982), the amount of P which will be lost to the environment can be estimated as 0.75 to 2.48 % of the feeding rate.

Although the amount of waste produced is largely a function of the rate of feeding applied, waste generation from a given amount of feed is controlled by feed conversion ratio (FCR). The FCR is in-turn determined by many factors related to biological and managerial aspects of an operation. One of these factor is the presence of uneaten feed. Recent laboratory studies on channel catfish by the authors (Malone and Chen) indicated that under controlled conditions, if all the feed input is eaten by the fish, the suspended solids waste generation is less than 20% of the feed input. In practice, if feed wasted runs from 5 to 20% of the applied feeds, as cited by Iwama (1991), the waste generation will be 30 to 40% of the feed input. This range is close to those reported by other investigators (Page and Andrews, 1973; Gordon, 1974, Ruane et al., 1977).

Characterization of the Liquid Waste Stream

Wastes produced due to fish excretion and uneaten food initially appears in fish tank and are removed either through the liquid waste stream or sludge waste stream. The liquid waste
stream refers to the direct wastewater discharge from the fish tank. The characteristics of the liquid waste are determined by the water quality in the tank. The water quality is largely determined by fish species being cultured, loading density, feeding rate, water exchange rate and the biofiltration and solids separation processes being employed. As a general observation, a system which supports healthy fish with the desired growth rate should have BOD₅ and TSS concentrations in the tank and liquid waste stream under 30 mg/L. In the United States, this quality of effluent could be directly discharged into most receiving waters, satisfying BOD₅ and TSS requirements. Nutrient concentrations in waters discharged from recirculating systems or from secondary sludge clarifiers are very high. Nitrate concentrations in excess of 100 mg-N/l and phosphorus concentrations in excess of 20 mg-P/l are common. Waters receiving these nutrients should be highly resistant to eutrophication. Although treatment of recirculating wastewater to control nitrogen level is technologically possible, phosphorus control is costly. Efforts in the United States are currently focused on the reduction of phosphorus levels in feeds as a means of controlling the effluent impact on environmentally sensitive rivers. Discharge to lakes and coastal waters with poor flushing characteristics will present problems. Effluents should be monitored and treatment processes developed in these nutrient sensitive areas.

Characterization of the Sludge Waste Stream

The waste solids generated within a recirculating system should be captured within the system by a solids separation process. The concentrated wastes can then be released from the system as sludge for further treatment and/or discharge. The mass of waste generated in a recirculating system is determined both by the amount of waste excreted and the extent of reduction by the biofiltration system. The extent of reduction is determined by treatment components in the recirculating system.

The amount of sludge production in a recirculating system is influenced by biodegradation of solids in the biofilter and water column by bacteria. The rapid removal of the solids from the system is desirable to reduce oxygen demand and ammonia-nitrogen loading rate on the system. However, minimization of solids degradation within the system implies an increase in the mass of sludge wasted from the system.

Easter (1992), characterized the effluent from a prototype recirculating production system for hybrid striped bass. A waste stream from the system was generated only during cleaning of the tube type clarifier. In the study, the clarifier was washed down after the application of 3 to 6.5 kg of feed to the system, usually once a day (Easter, personal communication). Total effluent volume was approximately 1892 liters per cleaning. Table 2 presents the average waste characteristics of the tube clarifiers wash down process for the 224 day study.

Different solids treatment components for recirculating systems result in different sludge volume for a given mass of waste generated. Table 3 presents a comparison of TSS concentrations in sludges resulting from different solids removal processes. Sludge volume is inversely proportional to the sludge concentration. And generally, the more concentrated sludges are more economical to treated and/or disposed of.

Another important aspect of sludge treatment is the relative quantities of the different sludge components. Table 4 shows the ratio between BOD₅, nitrogen and TSS of sludges generated by three systems using four different solids separation processes (Chen et al., 1991). These processes included pressurized sand filtration, upflow sand filtration, a clarifier under a rotating biological contactor (RBC) and an expendable granular biofilter (EGB). The variance in BOD₅ is due to the age of the sludge. The longer the solids stayed within the system, the lower the BOD₅/TSS ratio, implying a reduction in sludge volume. A low BOD₅/TSS ratio also is indicative of a sludge suitable for direct land application.
VI. ENVIRONMENTAL IMPACTS

The two principle problems associated with aquacultural waste are dissolved oxygen depletion and nutrient enrichment. The mechanisms of impact, method of correction, and associated costs differ significantly.

Dissolved Oxygen Depletion

Dissolved oxygen depletion in streams or impoundments is most frequently associated with the biochemical oxygen demand (BOD) of the discharged solids rather than the dissolved BOD of the water itself. Untreated discharges from ponds, raceways, and recirculating systems frequently display TSS levels well above those in adjacent waterways. Additionally, these solids have a high organic content which forecasts future oxygen consumption as degradation occurs. In turbulent conditions, the solid particles remain suspended and their impact is mitigated by high reaeration rates. Thus, moderate discharges can be tolerated with minor impact on all but the most oligotrophic systems. Lakes, quiescent bays, and slow moving streams, however, act as natural settling basins, forming sludge deposits which smother natural benthic communities and concentrate the waste. These bodies have little reaeration capacity, and increased oxygen consumption by sediments with the organic aquacultural wastes can rapidly induce severe oxygen depletions. Discharge of aquacultural effluents into lakes and reservoirs is ill-advised. Rivers and streams can generally be protected by clarification of the effluent streams by sedimentation processes.

Nutrient Enrichment

High in nitrogen and phosphorus concentration, aquacultural discharges threaten the trophic status of oligotrophic water bodies. Nutrient enrichment can dramatically alter the community of plants and organisms in receiving bodies of water, create an aesthetic algal bloom, and render water unacceptable for domestic consumption without costly water treatment processes. Lakes are extremely sensitive to nutrient enrichment. Nutrients are often recycled for months or even years, leading to cumulative impacts from even small discharges. Treatment of dilute aquacultural effluents, generated by ponds or raceways, for nitrogen and phosphorus is not economically feasible. The more concentrated waste streams generated by recirculating systems can be treated for nitrate removal, but phosphorus control would be very costly.

Other Concerns

Other potential environmental concerns frequently cited include release of therapeutics, fish, and pathogenic organisms which impair the natural communities. Clearly, release of fish species or genetic strains not natural to the area can have long term impacts. The impact of genetic commingling will become increasingly important as fish stocks become more domesticated. Although salinity and therapeutics in the effluent are of concern, rational site selection and good system management practices can work to mitigate the environmental impact. Ultimately, the control of pathogenic organisms can only be addressed by careful screening of broodstock or fingerlings. Once introduced, vectors for the spread of disease or parasites generally overwhelm containment measures. Natural purification processes or resistance of natural species can limit their impact; but a favorable response cannot be assured. Disinfection of effluents is a poor substitute for good disease control strategies in the production facility.

Recirculating Systems

Recirculating systems mitigate most of the potential environmental impacts by dramatically reducing the volume of water discharged. Suspended solids generally leave the facility as concentrated sludges that can be readily disposed of by land application, treated in small aerobic
sludge lagoons, or discharged to municipal treatment systems. Treatment of marine or brackish water sludge is also feasible utilizing salt acclimated anaerobic digestion processes.

Recirculating systems placed near sensitive aquatic ecosystems can be optimized for water reuse, permitting removal of nitrogen and phosphorus from concentrated effluent streams by the processes of denitrification and chemical additions, respectively. Use of alum, iron salts, or lime for phosphorus removal is costly and should be avoided where possible by careful site selection. In contrast, the large volumes of effluent water that are produced in flow-through systems are precluded from nutrient control by treatment economics. Ponds may avoid impacts on streams and rivers by seasonal control of discharges; eutrophication poses little threat during cold or wet months of the year.

Recirculating systems also reduce their threat of impact from release of chemicals, disease organisms, and genetic stocks through careful management of the systems' water. Generally not subjected to the vagaries of weather and bird predation, containment of genetic stocks are facilitated by enclosing recirculating systems. Additionally, disinfection of the lower volume effluent streams by ozone or ultraviolet light systems greatly reduces the potential for release of disease organisms.

Recirculating systems are not, however, a panacea. Careful site selection, facility design, and insightful management can provide a platform from which potential environmental impacts can be minimized.

VII. SUMMARY

Traditional aquaculture as practiced in the United States is a water intensive industry that produces organic and inorganic waste streams. High volume, low strength wastes are not easily treated with conventional wastewater technology. The impact of the additional oxygen demanding materials and excess nutrients in aquacultural wastewaters could be devastating to sensitive ecosystems.

The relief that recirculating technology provides from environmental impacts are three-fold. 1) Recirculating systems require only a fraction of the source water that pond or flow-through raceway technologies utilize. Reduced water demands will minimize competition between aquaculture and other industries for water use. 2) Recirculating systems have more controlled, lower volume and higher strength waste streams. Treatment of these wastes is more feasible with current technology. 3) Use of recirculating technology allows for more flexibility in facility siting. This will prove to be an advantage as environmental issues come to the forefront of societal concerns in the years to come.

VIII. REFERENCES


Note: Portions of this paper have been reproduced from T. Losordo, M. Masser, and J. Rokocy. 1992. Recirculating aquaculture tank production systems: An overview of critical considerations, Southern Regional Aquaculture Center Factsheet # 451, Stoneville, Mississippi, 6 p.
Table 1. General Water Quality Parameters for Recirculating Fish Culture Systems
(After Losordo, 1991a)

<table>
<thead>
<tr>
<th>Water Quality Parameter</th>
<th>Fish</th>
<th>Biofilter</th>
</tr>
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<tbody>
<tr>
<td>Dissolved Oxygen (mg/l)</td>
<td>&gt; 6.0</td>
<td>&gt; 4.0&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Carbon Dioxide (mg/l)</td>
<td>&lt;20</td>
<td>na</td>
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<tr>
<td>pH</td>
<td>6.0 - 9.0</td>
<td>7.2 -8.3&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Alkalinity (mg/l)</td>
<td>&gt;20</td>
<td>&gt; 100&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>NH&lt;sub&gt;3&lt;/sub&gt; (mg/l)</td>
<td>0.02 - 0.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>na</td>
</tr>
<tr>
<td>NO&lt;sub&gt;2&lt;/sub&gt; (mg/l)</td>
<td>0.2 - 5.0</td>
<td>na</td>
</tr>
<tr>
<td>NO&lt;sub&gt;3&lt;/sub&gt; (mg/l)</td>
<td>&lt; 500</td>
<td>na</td>
</tr>
</tbody>
</table>

<sup>a</sup>Kaiser and Wheaton 1983; <sup>b</sup>Malone and Burden 1988.

---

Table 2. Average waste characteristic values for a prototype hybrid striped bass
recirculating production system. (after Easter, 1992).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (mg / L)</th>
<th>Standard Deviation (mg / L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Suspended Solids</td>
<td>371</td>
<td>180</td>
</tr>
<tr>
<td>Volatile Suspended Solids</td>
<td>277</td>
<td>131</td>
</tr>
<tr>
<td>Filterable Suspended Solids</td>
<td>93.6</td>
<td>55.9</td>
</tr>
<tr>
<td>Chemical Oxygen Demand</td>
<td>320</td>
<td>102</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand</td>
<td>125</td>
<td>46</td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>Total PO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>Dissolved PO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>Total Ammonium Nitrogen</td>
<td>0.8</td>
<td>0.52</td>
</tr>
<tr>
<td>Nitrite (NO&lt;sub&gt;2&lt;/sub&gt; - N)</td>
<td>0.52</td>
<td>0.32</td>
</tr>
<tr>
<td>Nitrate (NO&lt;sub&gt;3&lt;/sub&gt; - N)*</td>
<td>178</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>*</sup> Peak value
Table 3. Total suspended solids concentrations in sludge generated by three typical solids removal processes (after Chen et al., 1991).

<table>
<thead>
<tr>
<th>Techniques</th>
<th>TSS Concentration in sludge</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upflow Sand Filter</td>
<td>0.005 - 0.015%*</td>
<td>Malone and Burden, 1988</td>
</tr>
<tr>
<td>Primary Sedimentation</td>
<td>1 - 6 %</td>
<td>Kugelman and Van Gorder (1991)</td>
</tr>
<tr>
<td>EGB</td>
<td>0.05 - 0.5%</td>
<td>Chen et al., 1991</td>
</tr>
<tr>
<td>Trickling Filter</td>
<td>0.06 - 0.09%</td>
<td>Metcalf and Eddy, 1979</td>
</tr>
<tr>
<td>Sand Filtration</td>
<td>0.01 - 0.02%</td>
<td>Metcalf and Eddy, 1979</td>
</tr>
</tbody>
</table>

* Calculated for 1-3 minute backwashing time

Table 4. The ratios of BOD5 and total nitrogen to TSS in aquacultural sludge from different recirculating systems (after Chen et al., 1991).

<table>
<thead>
<tr>
<th>System</th>
<th>BOD5/TSS</th>
<th>TKN/TSS</th>
<th>Animals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Sand Filter</td>
<td>0.20</td>
<td>0.053</td>
<td>Fish</td>
</tr>
<tr>
<td>Upflow Sand Filter</td>
<td>0.17</td>
<td>0.038</td>
<td>Turtle</td>
</tr>
<tr>
<td>EGB</td>
<td>0.09</td>
<td>0.049</td>
<td>Crawfish</td>
</tr>
<tr>
<td>EGB</td>
<td>0.35</td>
<td>-------</td>
<td>Fish</td>
</tr>
<tr>
<td>RBC Clarifier</td>
<td>0.09</td>
<td>0.061</td>
<td>Fish</td>
</tr>
</tbody>
</table>
Figure 1. Comparison of water use by four fish production systems on a per kg of production basis.
Figure 2. Required unit processes and typical components used in recirculating aquaculture production systems (after Losordo et al., 1992)