Water Quality in Identical Recirculating Systems Managed by Different Aquaculturists

K. Hanna[2], F. Wheaton[1], A. Lazur[3], S. VanKeuren[2]

[1]Environmental Science and Technology Department
University of Maryland
College Park, MD 20742, USA

[2] Biological Resources Engineering Department
University of Maryland
College Park, MD 20742, USA

[3] Center for Environmental Science
University of Maryland
Cambridge, MD 21613, USA

*Corresponding author: *fwheaton@umd.edu*

Keywords: Recirculating systems, system management, tilapia culture, water quality, management records

ABSTRACT

Water quality in recirculating aquaculture systems is a function of many variables including system design, loading, and management; temperature; feeding rate, and other variables. This research attempted to determine how different managers' management practices affected system water quality when the managers were using identical production systems. Water quality was monitored in two tanks on each of three farms, and an attempt was made to correlate management practices with the resulting tank water quality. The investigators worked with farm managers to collect as much data as possible about the management practices of each manager, economic data, when fish were placed into the tanks and when they were harvested, growth rates and other information. The resulting analysis proved there is great variation in water quality parameters in individual tanks both between farms and within a farm.

International Journal of Recirculating Aquaculture 11 (2010) 55-74.

The study showed that management of aquaculture systems had a strong influence on tank water quality. Operational data on economics, filter cleanings, fish growth and other information proved to be difficult to obtain as the managers did not keep detailed records of many of these variables. As a result, it was not possible to relate water quality to economics of the farm. It was apparent that good records are necessary for an aquaculture production facility if the operation is to be successful.

INTRODUCTION

Recirculating aquaculture systems are used throughout the United States and the world. Although economic considerations are a concern with recirculating systems, interest has remained high because of their potential benefits. System benefits include: 1) minimum water use that enables aquaculturists to raise salt water fish inland or increase the carrying capacity of a fixed water flow rate, 2) control of market timing and product size; 3) higher quality and/or more consistent quality of the product; 4) ability to produce aquatic products free from contamination by heavy metals, toxic organic compounds, and other potential toxins, 5) year-round production, and 6) the ability to satisfy markets requiring a continuous supply. Tremendous emphasis has been placed on the engineering aspects of these systems including; bio and mechanical filtration, circulation, oxygenation, heating and the like, in order to maintain high stocking densities, and make efficient use of energy and material inputs. However, a critical parameter whose importance has often been overlooked, is system management. It is likely that management practices are as important in determining the profitability of a recirculating aquaculture venture as the system design and equipment. Studies have shown how water flushing rates affect fish health (Davidson et al. 2009), and explored the effect of feed quality or feed content on water quality (Jisa et al. 1997). Unfortunately, there is little documentation on the qualitative and economic effects of various management practices on recirculating aquaculture system performance.

The study described herein attempted to determine the effects that three different management strategies (e.g. biomass or stocking densities, feed inputs, and water exchanges), have on recirculating system operation, maintenance, and profitability. These three parameters play a significant role in determining the profitability of an aquaculture operation and the overall water quality in the system.

Efficient use of the systems necessitates that biomass levels are kept at or near system capacity. Operating systems below their biomass capacity limits output and distributes capital (and in some cases, operating costs) over a smaller number of production units (fish). Production costs per unit (by weight) increase and profitability drops. Maintaining optimal biomass levels requires constant harvesting or transfer of fish from tank to tank as the fish grow. Handling increases the risk of injury, stress, and bacterial and fungal infections in the livestock; factors that can increase the risk of high mortalities and reduce growth rates. Lower biomass levels make it easier to maintain high water quality levels and fish health, and thereby reduce the risk of system failure. These factors must be continually balanced in management of recirculating systems.

Controlling the feed rate is an important management practice as it directly affects water quality and fish growth. The recommended feed rate varies between 1.5 and 15% of biomass weight per day depending on the stage of growth and the species of fish cultured (Losordo et al. 1992). Feed rates are maximized to maintain high growth rates, however waste production is directly proportional to feeding rates and feed quality. Higher waste production leads to lower water quality, which can impair growth.

The third management practice of importance in this study is that of water exchange frequency. Recirculating aquaculture systems are most often used when water supply is limited (Losordo et al. 1992). Recirculating systems offer an alternative to pond systems, typically using less than 10% of the water required in pond operations at an equivalent production level. Therefore, the conservation of water is one of the primary advantages of recirculating systems. Most recirculating systems are designed to replace no more than 5-10% of the system volume each day (Masser et al. 1999). These systems require constant filtration to maintain the high water quality standards needed for proper fish health. Higher water exchange rates reduce the need for filtration, however, the trade off is lower water use efficiency.

Each of these three management components (stocking density, feed rationing, and frequency of water exchange) have direct economic consequences. The costs of these management variables should be weighed against the resulting economic profitability. Unfortunately, clear cost-benefit analysis is often difficult to perform due to a lack of concrete data. This study looked at the effects of these three management factors on a wide range of measurable water quality variables, which have a direct impact on the health and growth of the fish and the quality of the fish produced.

METHODS AND MATERIALS

Aquaculture system

Figure 1. Sheriff tank in operation at an aquaculture production facility.

The aquaculture systems used at the three facilities involved in this study were engineered and manufactured by the same manufacturer, to the same specifications. The system was designed by Rick Sheriff (formerly of Opposing Flow Technology, Inc.) and is often referred to as the 'Sheriff Tank' (Figure 1).

Although the tanks can be constructed of aluminum or fiberglass, all tanks used in this study were aluminum and were operated by a regenerative blower air source. Air is introduced along the bottom of both long sides of the tank causing a flow upward along the outer tank walls, horizontally across the top of the tank, downward near the center of the tank, and outward along the bottom of the tank, enabling solids to migrate to openings positioned along the tank side and bottom juncture for collection in the biofilter section of the system. Thus, there are two circular flows across the cross section of the tank. In addition, water is drawn from one end of the tank, pumped through the filter on the other end of the tank, and returned to the tank on the end opposite the outlet. This causes a slow flow along the primary tank axis. The result of these two flow systems is two side-by-side helical flows in the tank with a slow movement along the axis of the helix and a more rapid flow around the two helixes. The tanks are thus completely and continuously mixed.

Air lift pumps are used to drive flow through the filters. The filters consist of a settling system and a biofilter. Many materials could be used for the filter media, but the Sheriff design uses PVC shavings such as are produced when turning a circular piece of PVC in a lath. The primary maintenance of the filters is to drain the filter section of the tank, wash it down to flush out the solids, and refill it with water. The tank and filter hold about 37,800 L (10,000 gallons) of water with the filter containing about 7,560 L (2,000 gallons) depending on the water depth in the tank. Due to incomplete draining of the filter during cleaning the system requires about 3,780 L (1,000 gallons) of replacement water after each cleaning. Design biomass for a fully loaded tank is about 2272 kg (5,000 pounds) of fish.

All farms included in this study grew tilapia, and each relied on ambient temperatures to regulate tank water temperature. Each farm used solid commercial feed pellets from different manufacturers, and included aquaculture as a part of their larger farm production. Because all farms used the same system hardware, any variation in water quality and economic profitability is attributable to differences in management practices at each of the recirculating aquaculture facilities. It was hoped, therefore, that a close examination of the operation of each of these facilities would shed light on critical management practices that make or break recirculating aquaculture production facilities, or alternatively show which practices had little effect on the economic viability of the operation.

Data collection

The study began with two commercial facilities, one of which ended production and went out of business halfway through the study. As a result, a third farm under different management was added to the study. Water quality parameters were measured and recorded on a weekly basis, but records of the daily management practices maintained by the farm managers were sparse and insufficient to meet the needs of the study. This "daily management" data included the time, frequency and volume of water exchange; daily feeding rate over time; addition of pH adjustment inputs; fish harvest quantities and dates, and biomass of the fish in the tanks over time; sale prices of the harvested product; cost and number of fingerlings added; and operational costs.[1]

---

[1] Operating costs were often combined with other operations on the farm.

Biomass data was available only periodically resulting in insufficient data being available to carry out an analysis. Thus, biomass values were estimated assuming a linear growth rate of 0.25 lbs/mo after a size of 0.5 lbs had been reached. The fish were purchased as fingerlings. It was assumed that the fish reached a size of 0.5 lbs after five months from time of purchase. The farm periodically recorded dates and quantities of fish harvested and the size of the fish, which allowed us to estimate the total biomass in each tank at that point in time. The data allowed the predicted growth rates to be checked against real data to ensure they were reasonable. These checks showed that the predicted growth rates were reasonable but considerable variation between predicted and actual weight data was apparent from tank to tank. The variation could have been due to incorrect weight data being reported or model prediction error. Daily feed rates were recorded by the farm manager as well as the number of filter cleanings involving water exchange. The amount of water exchanged with each filter cleaning was not always the same, but limited data required this assumption in order to get water exchange data.

Feeding, biomass and growth rates were collected from the farm mangers when the data was available. Weekly water quality parameters were measured by the project team from two tanks from each farm on a weekly basis. Measured water quality parameters included dissolved oxygen (DO), total solids (TS), ammonia, nitrate, nitrite, phosphate, pH and conductivity. Samples were taken from two tanks at each of three farms, for a total of six tanks. The sampling period for Farm 1 was between June 13, 2003 and October 30, 2003; for Farm 2 between February 13, 2004 and May 21, 2004; and for Farm 3 between July 24, 2003 and May 21, 2004.

Water quality

Alkalinity measurements followed the titration method outlined in Method 2320 (APHA 1995). Dissolved concentration of ammonia was measured using a Hach spectrophotometer model 4000, following Hach standard method 8038 for ammonia NH_3-N, which used the Nessler reagent, a corrosive oxidizer. Nitrite concentrations were measured using a Hach 4000 spectrophotometer (Hach, Loveland, CO, USA), following the Hach method 8507 (Hach 2000). Nitrate concentrations were measured using a Hach 4000 spectrophotometer, following Hach method 8039 (Hach 2000). Phosphate concentrations were measured using a Hach spectrophotometer (model 4000). Phosphorous values were measured in mg/L of phosphate (PO_4^{-3}). For samples made between the beginning of the study and August 28, 2003, Hach method 8048 was used. From September 5, 2003 until the end of the study, the method was changed to Hach method 8114, using molybdovanadate as a reagent (Hach 2003). Nearly all of the dissolved forms of phosphorous exist in solution as phosphates (APHA 1995). As with the nitrogen sample measurements, samples had to be diluted, as phosphorous levels were out of range for the Hach method employed.

When feasible, dissolved oxygen was measured promptly after the sample was taken. When not feasible, the sample bottle was filled completely and dissolved oxygen was measured within a few hours using a YSI® Model 55 Dissolved Oxygen Meter (YSI, Inc., Yellow Springs, OH, USA). All conductivity measurements were made using the YSI® Model 55, multi-meter. All sample pH readings were obtained directly using a Jenco® (Model 6071, Jenco Instruments, San Diego, CA, USA) pH meter and electrode. Total solids concentrations were determined using the method prescribed in the Section 2540B of Standard Methods (APHA 1995). Turbidity was measured using a Hach Portable Turbidity Meter (Model 2100P, Hach, Loveland, CO, USA) using a 'Ratio Optical System' (Hach 1998).

Statistical Analysis

The water quality parameters listed above were compared between each farm to determine if a qualitative difference existed between them that could be attributed to management practices. A regression was performed between each of these water quality parameters and the three independently measured management practices. These management practices include biomass, feed rate and water exchange rate. This analysis was conducted only on data obtained from Farm 3, as this was the only farm in the study that supplied sufficient information to conduct this analysis. Farm 2 and Farm 3 had shortened data collection periods that did not provide sufficient data due to Farm 1 going out of business. Regression analysis was conducted using the statistical analysis software package SAS version 8.0, using the MIXED procedure for ANOVA in SAS.

A second analysis of variance was performed comparing data between tanks. This analysis was to evaluate the variation in the different water quality parameters across all of the tanks sampled on the three farms.

RESULTS AND DISCUSSION

Table 1 gives the ranges of water quality parameters recorded for this study and the range of mean water quality parameters in individual tanks. These ranges were quite wide and reflected the lack of control of water quality parameters in the systems.

Oxygen, usually the most critical factor in recirculating culture systems, ranged from 1.8 to 9 mg/L in the tanks. Mean concentrations by tank ranged from 4.75 to 7.38 mg/L, while the standard error of the mean for the tanks ranged from 0.20 to 0.49. Rakocy (1989) recommends oxygen concentrations for tilapia remain above 5 mg/L; tilapia are well known to be able to tolerate lower oxygen concentrations. In those few instances where oxygen concentrations dropped below 4 mg/L in the tanks, the fish could have experienced some stress. Because there were no mass mortalities in any of the tanks monitored, the low oxygen did not appear to be fatal but could have caused some stress in the fish.

The pH values ranged from a low of 6.3 to a high of 8.5. The mean tank pH ranged from 7.03 to 7.51 while the standard error of the mean varied from 0.0615 to 0.0978. All pH values were within the tolerance range for tilapia and thus were not considered to be causing significant stress for the fish.

Total ammonia concentrations (TAN) are an important consideration because the unionized fraction (NH_3) is toxic to fish. Total ammonia concentrations in the tanks varied from essentially zero to a high of

Table 1. Variation in range of water quality parameters analyzed in this study.

Water Quality Parameter	Variation Range	Mean Tank Range
Total Ammonia Concentration (TAN)	0 – 17 mg/L	1.9-3.6 mg/L
Nitrate Concentration (NO_3)	0 – 180 mg/L	97 – 180 mg/L
Nitrite Concentration (NO_2)	0 – 7 mg/L	0.38 – 2.4 mg/L
Phosphate Concentration (PO_4)	0 – 180 mg/L	34 – 84 mg/L
Dissolved Oxygen Concentration	2 – 9 mg/L	4.75- 7.38 mg/L
Total Solids Concentration	300 – 3100 mg/L	670 – 1500 mg/L
pH	6.0 – 8.5	7.03 – 7.51

17 mg/L. Mean values varied from 1.9 to 3.6 mg/L while the standard error of the mean varied from 0.18 to 0.64. This suggests that the very high ammonia concentrations were of short duration and were not generally a continuing problem. However, even short duration spikes can create stress and reduce growth rates and/or lead to disease outbreaks a few days after exposure. Rakocy (1989) gives the upper ammonia tolerance for tilapia as 2 mg/L of NH_3-N, but Chapman (1992) suggests a limit of 1 mg/L of TAN (total ammonia nitrogen) as the upper limit for the culture of tilapia. Using Rakocy's values and converting this 2 mg/L of NH_3–N to total ammonia at a pH of 7.5 and 23°C gives a limit of approximately 115 mg/L total ammonia (TAN). At a pH of 8.0 and the same temperature the equivalent total ammonia is 37 mg/L and at a pH of 8.5 it is 13 mg/L. For the ammonia conditions measured in the tanks, high stress would only be caused when pH values approaching 8.5 were accompanied by some of the higher ammonia levels recorded. However, if Chapman's suggested limit is used, the fish experienced considerable stress throughout the data collection period. Insufficient data are available to determine if the fish in this study were stressed or not.

Nitrite concentrations (NO_2) in the tanks generally remained below 2.5 mg/L except in two cases when nitrite concentrations reached 7 and 4 mg/L, respectively. The mean nitrite concentrations in the tanks ranged from 0.38 to 2.4 mg/L with the standard error of the mean ranging from 0.038 to 0.65. Rakocy (1989) states that tilapia begin to die when nitrite concentrations reach 5 mg/L as NO_2-N. Because there were no die offs in the two tanks having 7 and 4 mg/L of nitrite, the fish appear to be able to tolerate higher nitrite concentrations, at least for short time periods and at the pH experienced in the tanks. There is a good chance that the fish experienced stress at these high levels, but there was no negative result measured in the data collected.

Nitrate (NO_3) is relatively less toxic than nitrites to fish, but can be toxic at higher concentrations (e.g. 400 mg/L or higher, Timmons et al. 2001). Nitrate concentrations in the tanks ranged from essentially zero to 320 mg/L. The mean values of nitrate concentrations for the tanks ranged from 97 to 180 mg/L, while the standard error of the mean ranged from 7.3 to 14. None of these concentrations should create fish stress. Water changes were used by the aquaculturists to limit nitrate concentrations.

Phosphate (PO_4) concentrations are not normally considered to be toxic to fish in recirculating systems. It was monitored in this study primarily to determine the phosphate concentrations in wastewater from these systems. Because there was no usable method of measuring the solids lost during filter washing, it was not possible to develop either a nitrogen or a phosphorous balance for the systems. Thus, the phosphate concentrations measured were concentrations in the culture water. Considerable variation in the phosphate concentrations in the water were observed varying from 1 or 2 to over 170 mg/L of phosphate. Mean concentrations in the tanks varied from 34 to 84 mg/L while the standard error of the means varied from 3.2 to 10.

System alkalinity was controlled by the aquaculturists, usually by adding sodium bicarbonate or some other base. The base was added manually and periodically, and one system used a slow injection that was manually controlled. Alkalinity varied from 25 to over 360 mg/L as $CaCO_3$. The mean values for the various tanks varied from 88 to 220 mg/L as $CaCO_3$ while the standard error of the means varied from 12 to 22. Most authors recommend alkalinity in recirculating systems should be maintained above 50 to 100 mg/L as $CaCO_3$. Chapman (1992) gives an acceptable alkalinity for tilapia as 50 to 700 mg/L. Although the alkalinity was relative low at times in some tanks it does not appear to be a major problem in the systems as pH did not suddenly drop.

Turbidity values ranged from 1 to 79 NTU with the mean values varying from 7.80 to 43.3 NTU. The standard error of the mean for turbidity varied from 0.668 to 5.31. Although this is considerable variability, it is within the acceptable range for tilapia.

Conductivity data is not normally a consideration in fish culture, except as an indirect measure of salinity. Conductivity values over the course of the study did not appear to be out of the reasonable range for these freshwater fish. Thus, salinity was not a limiting factor in these studies.

Total solids ranged from 3,100 to a low of about 300 mg/L. The mean values for total solids for the tanks varied from 670 to 1,500 mg/L while the standard error of the mean varied from 39 to 200. Chapman (2000) suggests that total solids be maintained between 25 and 100 mg/L. However, this recommendation is based on what is desirable and may not reflect the acceptable tolerance limits for tilapia. The effect of solids on fish is mostly related to negative consequences resulting from gill irritation. The type of solids (e.g. silt or organic material) and several other variables affect the concentration of solids the fish can tolerate. In this study, no obvious negative effects were evident from high solids concentrations, and no gill tissues were assayed.

The weekly water quality values varied widely. The analysis of variance results verified this observation, showing a significant difference (at the 0.05 level) between tanks in the values obtained for all water quality parameters measured with the exception of ammonia (Table 2). This indicates the significant impact that management practices have on water quality, given that each tank was identical. Each aquaculturist managed his individual tanks approximately the same. However, each of the farmers had different management methods, most of which varied with time. The ultimate result is an understanding that the management of a recirculating system may be every bit as important as good system design, and possibly more so.

Regression curves were drawn plotting measured water quality parameters with each of the three management practices emphasized in this study: biomass, feed rate, and water exchange rate. Some trends were observed, although the high variability produced relatively low

Table 2. ANOVA ('MIXED' procedure) results on water quality parameters for the three farms operated using the same tanks but different managers.

ANOVA:	Numerator DF	Denominator DF	f-value	Probability	Significance
pH	5	144	4.43	0.0009	Significant
Nitrate	5	138	7.04	<0.0001	Significant
Nitrite	5	142	8.95	<0.0001	Significant
Phosphate	5	137	5.63	<0.0001	Significant
Ammonia	5	137	2.19	0.0584	Not Significant
DO (mg/L)	5	108	6.95	<0.0001	Significant
Total Solids	5	118	7.88	<0.0001	Significant
Alkalinity	5	110	5.65	0.0001	Significant
Conductivity	5	119	5.41	0.0002	Significant
Turbidity	5	142	33.64	<0.0001	Significant

R^2 values, leaving few statistically significant regressions. Table 3 shows the significance of the regression coefficients for all regressions. A projected growth curve was used to estimate biomass data between measurements, however, limited or missing biomass removal data made this sort of assessment difficult. When comparing biomass data, where it was available, to the model growth rate, the model biomass values were slightly higher. An economic analysis was not attempted due to lack of sufficient economic data. The collection of this sort of data was complicated by the fact that in each case the aquaculture production was a part of a larger agricultural enterprise. Therefore, labor and operating cost could not be accurately separated for each of the components of the farm.

Table 3. Significance of regression parameters analysis of tanks 1 and 2 of Farm 3 for biomass, feed rate and water exchange rate. All values less than 0.05 are significant.

Regression Parameter	**Biomass**		**Feed**		**Water Change**	
	Tank 1	**Tank 2**	**Tank 1**	**Tank 2**	**Tank 1**	**Tank 2**
pH	0.0492	0.3023	0.1755	0.0007	0.9832	0.8175
Nitrate	0.2491	0.7930	0.0920	0.1413	0.6142	0.8714
Nitrite	0.0005	<0.0001	0.0003	0.2125	0.0878	0.6985
Phosphate	<0.0001	<0.0001	<0.0001	0.0158	0.1524	0.0923
Ammonia	0.0150	<0.0001	0.0323	0.3102	0.3101	0.8891
Dissolved Oxygen	0.0023	0.0096	<0.0001	0.5175	0.4915	0.3108
Total Solids	0.0006	0.0210	0.0001	0.0313	0.9832	0.8081

Figures 2-6 show the regression of each of the water quality parameters versus biomass, feed rate, and water exchange rate for the data for Farm 3, as this was the only farm in the study that supplied sufficient information on biomass levels, feeding rates, and water exchange rates to conduct this sort of analysis. Only those variables found to have a significant regression (slope greater than zero) against any of the three primary management indicators were plotted. Figure 2 presents a regression plot for the total solids versus feed; while Figures 3-6 present regression plots of nitrite, phosphate, dissolved oxygen and total solid concentrations versus biomass, respectively. The aquaculturist from

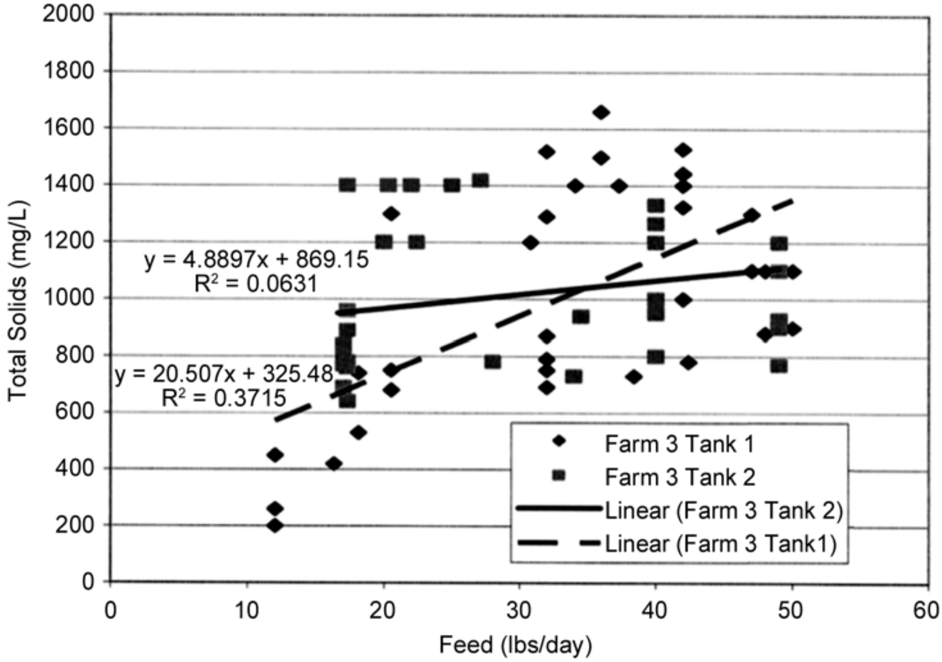

Figure 2. Regression of total solids versus feed for Farm 3.

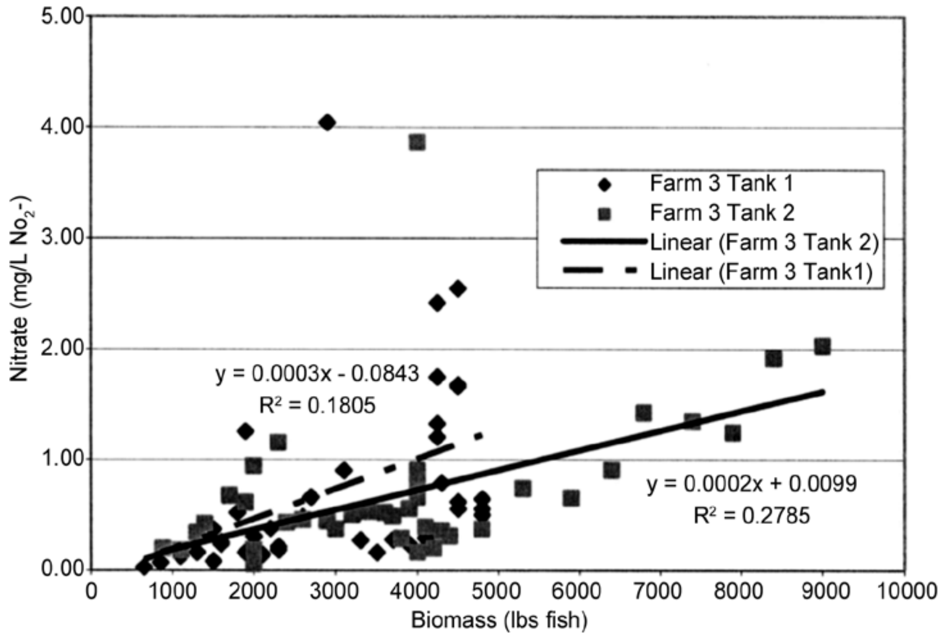

Figure 3. Regression of nitrite versus biomass for Farm 3.

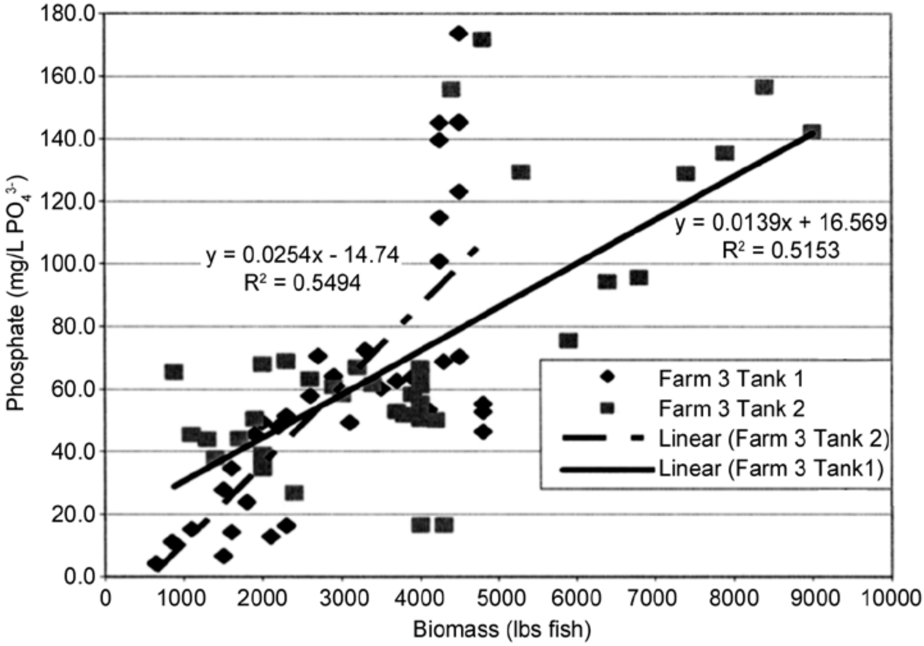

Figure 4. Regression of phosphate versus biomass for Farm 3.

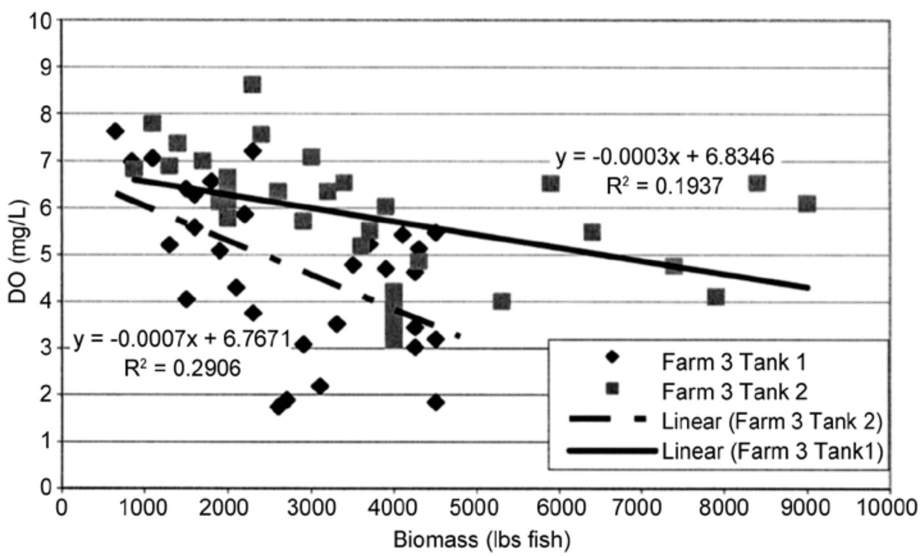

Figure 5. Regression of dissolved oxygen (DO) versus biomass for Farm 3.

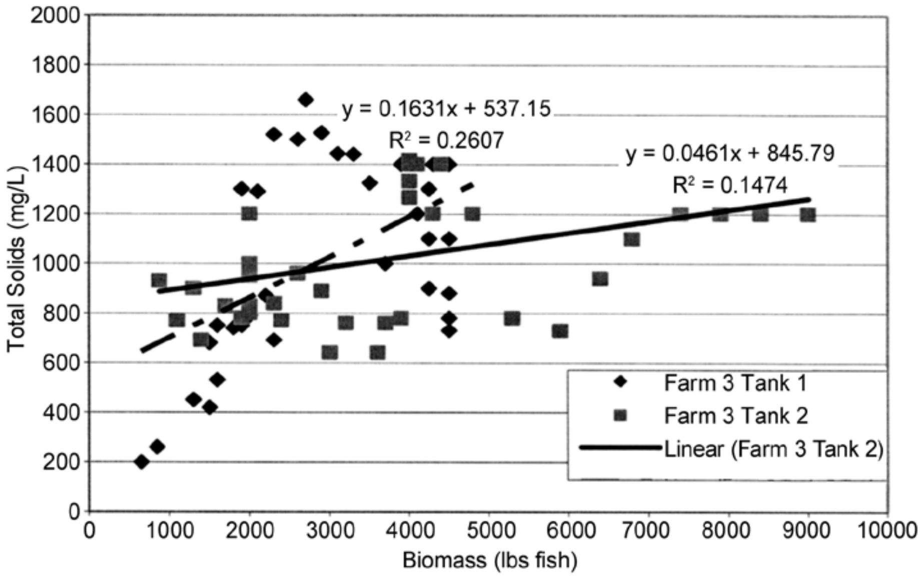

Figure 6. Regression of total solids versus biomass for Farm 3.

Farm 3 believed he was managing both tanks 1 and 2 in the same way. The data, however, suggested there were differences in what was happening in the two tanks, but it was not possible to quantitatively define these differences.

Biomass was shown to have a significant impact on all measured water quality parameters, with the exception of nitrate. Feed was shown to have a significant impact on all water quality parameters in at least one of the two tanks from Farm 3. This is not surprising when one considers that feed is the primary cause of water quality impairment, and is directly tied to the stocking density of each tank. The farms did manage biomass when it became too high, but management was more in response to necessity than following a systemic plan.

In contrast, water exchange rate was found to have no significant impact on any of the water quality parameters measured in this study. This may be due to the relatively consistent frequency and quantity in which water changes occurred resulting in a very narrow range of exchange volumes to which water quality parameters could be compared.

It has been emphasized above that profitability of recirculating systems depends on maintaining stocking densities as close to system capacity as possible, essentially 100 percent of the time. Tank biomass recorded in this study varied from less than 454 to over 4090 kg (1,000 to over 9,000 pounds), with the upper end probably being an overestimate of production because the tanks' carrying capacity was between 2,272 and 2,727 kg (5,000 and 6,000 pounds). A highly variable biomass in the production tanks shows that the tanks were often operated well below capacity. Because tank depreciation and operating costs are virtually the same for both high and low stocking densities, it is most cost effective to operate tanks at or near capacity in order to lower per unit costs. Stocking densities beyond tank capacity will lead to higher waste production and oxygen consumption, ultimately leading to reduced fish health and growth and increased mortality, negatively affecting production.

Maintaining stocking densities at or near capacity throughout the year requires the farm manager to continually add or remove fish as the fish grow and are harvested. This is labor intensive and requires careful planning and record keeping. In addition, handling the fish also increases fish stress levels and increases the risk of disease and mortality. Ideally, data on biomass levels would be linked to production in order to determine the optimal biomass level based on economic considerations. However, in this study it was impossible to obtain adequate financial records, or distinguish the production costs of the aquaculture tanks from the rest of the farm facility.

Feed is closely tied to biomass but is distinguished from it in that feed levels must be balanced against the need to not feed excessively, resulting in higher waste loadings, and the need to maintain high growth rates. For both tanks on Farm 3, phosphate and total solids were significantly affected by feeding rate, increasing with increasing feeding levels, while pH, nitrate, nitrite, ammonia and dissolved oxygen were found to be significantly affected in one or the other of the two tanks studied. Dissolved ion levels were found to increase with increasing feed, while oxygen levels were lower when associated with higher feeding rates, as would be expected given the microbial degradation of suspended particles.

Throughout this study water exchange frequency (frequency of cleaning the filter) was not found to significantly impact any of the water quality variables measured. This may be due in part to two reasons. First, it is apparent that other factors, such as feed rate and biomass, had a more significant impact on water quality, which may have overshadowed the effects of water exchange. Secondly, the water exchange frequency data was available for only one farm, or rather two tanks under the same farm manager. As a result, the frequency of water exchange was fairly consistent as determined by the habits, standards and practices of the farm manager. To more clearly define a regression for each of the water quality parameters and the water exchange frequency it would be necessary to compare systems with widely different water change frequencies in order to more easily define regression variables.

CONCLUSIONS

Overall, the study shed light on significant differences between water quality parameters and current management practices of various aquaculturists. Consistent with management practices and attitudes, it was also found that farm managers varied significantly in their approach to recordkeeping, as well as in the detail and reliability of the information contained therein. If these management variables are to be properly evaluated, it is necessary that similar studies be conducted under more controlled conditions with accurate and detailed records being maintained at all times. Likewise, it is critical that these studies be linked with actual production costs and the ultimate yield or profit from said production, under similar circumstances and market conditions. The three aquaculturists participating in this study did not keep detailed records of their production variables or of their costs and expenses. Therefore inadequate records prevented historical tracking of costs, income and profitability; or improvements in management practices of the enterprise.

Although much of the data needed to draw definitive conclusions regarding the role of management practices on specific water quality variables were sporadic, the study demonstrates the value and necessity of proper management practices. It was determined that nitrite, ammonia, and phosphate concentrations increase with increasing biomass levels within the fish tanks, which is directly correlated to feeding levels. Conversely, dissolved oxygen levels tend to decrease with increasing biomass or feeding levels. No statistically significant correlations were observed between water exchange volumes and the water quality variables measured in this study. With the single system type employed in this study proper management appears to be as important, if not more important, than the system hardware itself, and is a must for any recirculating system to function properly and be economically viable.

Along with good management comes proper and accurate record keeping, which is an absolute must if any aquaculturist wishes to be successful and profitable. To achieve high productivity, recirculating aquaculture systems must be optimized. Optimization can be defined as the highest productivity attainable given the limitations of the system; therefore, an optimized system is, by definition, a system of checks and balances that can only be achieved through proper management and accurate recordkeeping.

ACKNOWLEDGEMENTS

This project was funded by the Maryland Agricultural Experiment Station and the University of Maryland. The authors wish to express their appreciation to the three commercial aquaculture farmers that generously allowed the research team to sample their systems. Without their cooperation this project would not have been possible.

REFERENCES

APHA **1995**. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association: Washington, D.C., USA.

Chapman, F.A. **2000**. Culture of Hybrid Tilapia: A Reference Profile. Circular 1051. Department of Fisheries and Aquatic Sciences, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL, USA.

Davidson, J., Good, C., Welsh, C., Brazil, B., and Summerfelt, S. **2009**. Heavy Metal and Waste Metabolite Accumulation and their Potential Effect on Rainbow Trout Performance in a Replicated Water Reuse System Operated at Low or High System Flushing Rates. *Aquacultural Engineering* 41:136-145.

Hach Company **1998**. Portable Turbidity Model 2100P Instrument and Procedure Manual. Publication Cat. No. 46500-88. Loveland, CO, USA.

Hach Company **2000**. DR/2010 Spectrophotometer Handbook. Loveland, CO, USA.

Hach Company **2003**. DR/4000 Spectrophotometer Handbook. Loveland, CO, USA.

Jirsa, D.O., Davis, D.A., and Arnold, C.R. Effects of Dietary Nutrient Density on Water Quality and Growth of Red Drum, *Sciaenops ocellatus,* in Closed Systems. *Journal of the World Aquaculture Society* **1997**, 28(1):68-78.

Losordo, T.M., Masser, M.P., and Rakocy, J. **1992**. Recirculating Aquaculture Tank Production Systems: An Overview of Critical Considerations. SRAC Publication No. 451. Southern Regional Aquaculture Center. Mississippi State, MI, USA.

Masser, M.P., Rakocy, J., and Losordo, T.M. **1999**. Recirculating Aquaculture Tank Production Systems Management of Recirculating Systems. SRAC Publication No. 452. Southern Regional Aquaculture Center. Mississippi State, MI, USA

Rakocy, J.E. **1989**. Tank Culture of Tilapia. SRAC Publication 282. Southern Regional Aquaculture Center, Mississippi State, MI, USA.

SAS **1999**. SAS Online Documentation: Version 8. http://v8doc.sas.com/sashtml. SAS Institute Inc. Cary, NC, USA.

Timmons, M.B., Ebeling, J.M., Wheaton, F.W., Summerfelt, S.T., and Vinci, B.J. **2002**. Recirculating Aquaculture Systems. Northeastern Regional Aquaculture Center Publication No. 01-002. Cayuga Aqua Ventures, Ithaca, NY, USA.