PROJECT COMPLETION REPORT

97-6 "Optimizing Removal of Settleable Solids Using a Non-Proprietary Double-Drain for Circular Culture Tanks"

Termination Report Period: July 1, 1997 – January 31, 2000

NRAC Total Funding: $79,813 (July 1, 1997 – January 31, 2000)

Principal Investigator: Dr. Michael B. Timmons, Cornell University, Ithaca, NY &
Dr. Steven T. Summerfelt, Conservation Fund Freshwater Institute,
Shepherdstown, WV.

Part I: Summary of Project and Accomplishments

Project Objectives:

The overall goal of this project was to improve the methods used to remove settleable solids from the waste stream discharge and/or from the water column of the rearing system. The specific objectives were:

1. To evaluate the removal of settleable solids from the tank water column for round tank configurations, as it is affected by the tank hydraulic retention time, direction of flow (exit fraction from center bottom versus outside edge), and tank depth-to-diameter ratios.

2. To quantify the economic impacts of solids removal, equipment costs, and retention time on cost of production.

3. To extend the results by producing an NRAC bulletin on solids removal techniques from tanks; conduct a workshop targeting commercial aquaculturists and designers on solids removal, that includes the research findings of this study; and develop an interactive software package that analyzes the economic impacts of solids removal techniques and other management options and associated costs. The software package will be made available through the NRAC extension network as a software and operating manual package that calculates costs of production as affected by the various design and operating decisions.

Anticipated Benefits:

The results obtained in this study are generally applicable to both flow-through and water reuse systems, for both warm and coldwater finfish species. Improving the solids removal efficiencies from conventional systems can reduce occurrence of fish health problems and is the primary method by which discharges of phosphorus and other nutrients can be minimized. For example, raceways have been traditionally used to raise coldwater fish such as rainbow trout, but raceways are not the ideal culture vessels when fish health, water use, water quality, and waste management issues are present, especially when phosphorus control is a real issue. To avoid water use limitations and strict waste discharge limits, as well as to provide a healthier and more efficient culture environment, this project has focused on improving intensive culture within circular culture tanks. Improvements in the efficiency and cost effectiveness of solids removal for intensive circular tank culture systems are key attributes to increasing economic productivity. The end-users of the findings of this research are the commercial growers, consultants, and industry support leaders that focus on the production of finfish in the Northeast region.

Principal Accomplishments:

Objective 1. Experiments on Solids Removal from Double-Drain Culture Tanks

Settleable solids removal from 'Cornell-type' double-drain tanks was investigated at Cornell using tilapia and at the Freshwater Institute using rainbow trout. Fish densities were 60 kg/m^3 and fish were fed 1% body weight per day. To more precisely quantify the rate of settleable solids flushing, experiments were carried out where pulses of sinking PVC cylindrical beads were added to the "Cornell-type" dual-drain culture tank. The sinking PVC cylindrical beads (3 mm in diameter, with a specific gravity of 1.05 times that of water) were used for exact quantification of settleable solids flushing from circular tanks.

Replicated bead flushing tests were used to determine the influence of hydraulic exchange rate (1 and 2 rearing tank volume exchanges per hour), diameter-to-depth ratio (12:1, 6:1, 3:1), and the percentage of flow leaving the bottom center drain (5, 10, and 20% of total flow) on solids flushing characteristics. The bead flushing data was analyzed using the solution to a non-steady-state mass balance. This analysis will quantify the amount of solids flushing that occurs through the bottom center drain and that which was due to simple dilution versus solids transport produced by settling and radial flow dynamics.

Fish were found to have a large influence on solids flushing. Therefore, the Freshwater Institute also completed companion tests without fish to quantify how the presence of fish improved settleable solids transport out of the "Cornell-type" culture tank. Cornell has already completed tests on settleable solids flushing in tanks that did not contain fish.

Total suspended solids (TSS) concentrations were also measured in bottom and sidewall discharges and in the effluent from a commercial microscreen filter treating the bottom flow. Mean results from data collected at the Freshwater Institute indicate that the 'Cornell-type' double-drain tank concentrated the majority of TSS in the bottom flow. The TSS concentration discharged through the bottom drain has averaged 19.6 ± 3.6 mg/L (± standard error), while the TSS concentration discharged from the sidewall has only averaged 1.5 ± 0.2 mg/L. Throughout this report, we consider that the sidewall concentration of TSS is a reasonable approximation of the TSS concentration in the fish rearing tank and that these two terms (sidewall concentration and tank concentration) can be used inter-changeably. The sidewall discharge, which contained 80-95% of the total flow, but only 1.5 mg/L TSS, would probably not require any further treatment and most likely could be discharged directly under most state and federal regulations. Further treatment of the bottom discharge across a commercial microscreen filter then captured 82% (± 4%) of the TSS in the bottom discharge, so that only an average of 3.5 ± 0.8 mg/L TSS would be discharged with the bottom flow.

When using the Cornell Double-Drain approach, the bottom flow is only 5-20% of the total tank discharge, so it would be possible to further treat this flow with finer microscreen filters or using settling tanks, wetlands, or sand filters, if required by stringent state or federal discharge regulations. Therefore, conventional flow-through systems that use circular culture tanks installed with the 'Cornell-type' dual drain configuration can capture more of the waste solids and phosphorus from the water flow than can be captured within typical raceways operation that contain quiescent zones and off-line settling ponds. Additionally, when the 'Cornell-type' dual drain tank is used within partial-recirculating systems, these systems are capable of supporting high production densities while providing uniformly healthy water quality, optimized water velocities, and efficient, rapid, and gentle solids removal (Freshwater Institute, unpublished data). This type of partial recirculating system would be able to capture roughly 80-95% of the total waste solids produced, which is significantly better waste capture than is typically achieved within raceways operated under serial water reuse (e.g., 50% solids capture [Mudrak, 1981]). Also, the solids filter treating the discharge from the partial-reuse system would be relatively small and inexpensive compared to a similar unit scaled to treat the much larger flow discharged from a raceway operation of relatively similar annual fish production.

Objective 2. Economic Evaluation of Solids Removal

A software package was developed as part of this project and was made available through the Cornell Summer Short Course. Sample input and output results are given in the Appendix. This Excel program is quite useful in looking at any combination of input costs for equipment, e.g. micro-screen filter, their impact on floor space required (affects size of building), and overall investment costs. The program distinguishes between building investment and equipment investment since the depreciation periods are different for these two categories of capital investment. The excel program expresses overall costs ($/lb) and gives a breakdown of individual costs ($/lb) contributing to overall costs, e.g.

- Electric
- Feed
- Water heating
- Air heating
- Oxygen
- Labor
- Interest, repairs and depreciation
- Fingerling

The above costs are then made a function of overall feeding rates (lb/day) being fed into an individual tank system (an assumed feed to gain ratio is also required). See Appendix for sample outputs. The Cornell Short Course was a big success (Flyer describing the 1999 course is provided in the

Appendix) and will be repeated in the summer of 2000 as an annual event. This short course is one of the main mechanisms by which we incorporate recent research findings and extend them into the aquaculture community. The short course is well attended by aquaculturalists in the Northeast, the US and Canada and several out-of-country professionals (attendance is in the 24 to 34 range, and is intentionally kept small to emphasize one-on-one interactions and hands-on activities).

The influences of culture tank design variables on fish farm profitability were also presented in a paper at *The Second International Conference on Recirculating Aquaculture* in 1998. This paper is provided in the Appendix (Summerfelt,* S.T., M.B. Timmons and B.J. Watten. 1998. Culture tank designs to increase profitability. Pages 253-262 In: *The Second International Conference on Recirculating Aquaculture*, G.S. Libey and M.B. Timmons (eds.), Virginia Polytechnic Institute and State University, July 16-19, Roanoke, VA).

Objective 3. Extend the Results of Double-Drain Culture Tank Technology

The PI's preliminary research has been submitted and published in the journal *Aquacultural Engineering*. Two other papers entitled, "Culture tank design to increase profitability" and "An integrated approach to aquaculture waste management," were published in the proceedings of the *Second International Conference on Recirculating Aquaculture Systems*, July 18, 1998 in Roanoke, Virginia (5 copies are provided of all papers published as part of the final report). We have also written a summary paper on raceway and culture tank management:

> Summerfelt, S. T., M. B. Timmons, and B. J. Watten. 2000. Raceway and Tank Culture. In: R. R. Stickney (ed.), *Encyclopedia of Aquaculture*, John Wiley and Sons, Inc., NY.

This just-published work will also serve as an excellent extension type bulletin on this subject and is considered a project deliverable in this area. The PI's are also distributing:

> Timmons, M.B., S.T. Summerfelt, and B.J. Vinci. 1998. Review of circular tank technology and management. *Aquacultural Engineering* 18(1):51-69.

This paper is proving to be a very effective publication to provide a succinct review of round tank management, solids control, and selection of engineering parameters affecting tank design. The PI's have received frequent requests for their culture tank papers and these papers are being distributed to the general public thus serving effectively as extension bulletins, particularly for the engineering and technical audience.

The PIs are currently completing a manuscript to submit to the journal *Aquacultural Engineering*, which will detail and discuss the experimental methods and findings that are shown below (in Part II of this report). These results were presented at an Aquacultural Engineering Society meeting in Raleigh, NC in a 3 day meeting November 1999. Again, this was a mechanism to distribute the results very rapidly into the engineering community.

> Summerfelt,* S. T., J. Davidson, M. B. Timmons. 1999. Hydrodynamics in the 'Cornell-type' dual-drain tank. *Aquacultural Engineering Society Issues Forum*. November 4-6, Raleigh, NC.

IMPACTS:

We believe that this project has already had a very significant impact on aquacultural management. The Cornell- double-drain as demonstrated and analyzed in this NRAC study is being rapidly adapted throughout North American continent (see Table 1.1 as a partial listing of those farms we know have adapted this design approach). In addition, the following outputs have been achieved:

1. Peer-reviewed publications (see listing attached at end of Part I of this report) Produced an extension type bulletin publishing techniques for removal of suspended solids from tank and raceway systems (Summerfelt, S. T., M. B. Timmons, and B. J. Watten. 2000. Raceway and Tank Culture. In: R. R. Stickney (ed.), *Encyclopedia of Aquaculture*, John Wiley and Sons, Inc., NY)
2. Software and user's manual to analyze design and management options for solids removal (available through Cornell short course)
3. Economic analysis of solids removal techniques (through Cornell summer short course)
4. Workshop session on solids removal from intensive raceway and tank culture systems in 1998 in conjunction with the Aquacultural Engineering Society

Researchers at both Cornell University and the Freshwater Institute have worked to transfer the

'Cornell-type' dual-drain culture tank design to industry. Several commercial fish farms have adopted the dual-drain circular culture tank technology and at least two consulting/manufacturing firms (PRAqua Technologies Ltd., Nanaimo, British Columbia, Canada; and Marine Biotech Inc., Beverly, MA) have begun incorporating the technology into fish farm designs. Fish farms are adopting the "Cornell-type" dual-drain culture tank design to improve the efficiency of solids removal from the system and to concentrate solids within a much smaller discharge. Treatment costs of discharge are basically proportional to volume, so the reductions in discharge become direct savings in operational costs. Also, the 'Cornell-type' dual-drain culture tank design is used within coldwater reuse systems to rapidly flush settleable solids from the system using a flow equivalent to the system's make-up flow, i.e., about 5-20% of the total reused flow. The bottom drain flow flushes fecal matter and waste feed from the system in a matter of only minutes, which removes the waste particles from the system before they can degrade into smaller particulate matter (which is harder to remove) or leach nutrients into the water column.

On average, the flow discharged from the bottom drain contained TSS concentrations (19.6 ± 3.6 mg/L) that were more than 10-times greater than the TSS concentration discharged from the side wall drain (i.e., 1.5 ± 0.2 mg/L). This concentrated and relatively small flow discharged from the system is easy to treat using a microscreen filter. The microscreen filter used at the Freshwater Institute removed greater than 80% of the TSS from the bottom drain discharge water. Thus, discharge of the post-screened effluent would be typically less than 4 mg/L without dilution or further flocculation and the option of using finer screens would also be an option to further reduce TSS in effluent flows.

Recommended Follow-up Activities:

Further studies are recommended to demonstrate the significant improvements that can be made in culture tank water quality and in overall waste management when the 'Cornell-type' dual-drain tank is used within partial-reuse and fully-recirculating systems for the culture of coldwater species. Recognizing this opportunity, the Freshwater Institute has already begun researching these issues within two quasi-commercial scale systems located at the Freshwater Institute's new facilities outside of Shepherdstown, WV. This additional research on the application of the 'Cornell-type' dual-drain culture tank within coldwater recirculating systems is being supported by a grant from the USDA-ARS.

Publications, Manuscripts, And Papers Presented:

Papers Presented. The following paper presentations have resulted (at least in part) from this NRAC funding (* indicates the presenting author):

- Summerfelt,* S.T. 1998. Production intensification and water reuse. In: *Management Principles for Coldwater Fish Production*, Freshwater Institute, July 30, Shepherdstown, WV.
- Summerfelt,* S.T. 1998. An integrated approach to aquaculture waste management in flowing water tank culture systems. Pages 87-97 In: *The Second International Conference on Recirculating Aquaculture*, G.S. Libey and M.B. Timmons (eds.), Virginia Polytechnic Institute and State University, July 16-19, Roanoke, VA.
- Summerfelt,* S.T., M.B. Timmons and B.J. Watten. 1998. Culture tank designs to increase profitability. Pages 253-262 In: *The Second International Conference on Recirculating Aquaculture*, G.S. Libey and M.B. Timmons (eds.), Virginia Polytechnic Institute and State University, July 16-19, Roanoke, VA.
- Summerfelt,* S.T. 1999. Waste Capture. *Trout Farm Waste Management Conference*. North Carolina State University's Mountain Horticultural Crops Research and Extension Center, May 12, Asheville, NC.
- Summerfelt,* S.T. 1999. Systems Overview. *5th Annual Aquaculture Water Reuse Systems Short Course*. Cornell University, June 22-26, Ithaca, NY.
- Summerfelt,* S. T. 1999. Recirculating technologies typically used to culture cold water species. *Aquaculture Canada '99*. October 26-29, Victoria, BC, Canada.
- Summerfelt,* S.T., M.B. Timmons and B.J. Watten 1999. Recirculating rearing techniques and issues. In: Aquacultural Engineering Society Training Workshop. (Presentation notebook available from AES, Shepherdstown, WV), *Aquaculture America '99,* Tampa, FL, January 27-29.

- Summerfelt,* S. T., J. Davidson, M. B. Timmons. 1999. Hydrodynamics in the 'Cornell-type' dual-drain tank. *Aquacultural Engineering Society Issues Forum*. November 4-6, Raleigh, NC.

- Timmons,* M.B. and S.T. Summerfelt. 1997. Advances in circular culture tank engineering to enhance hydraulics, solids removal, and fish management. Pages 66-84 In *Recent Advances in Aquacultural Engineering* (Proceedings), M.B. Timmons and T.M. Losordo (eds.), Aquacultural Engineering Society Annual Meeting, November 9-12, Orlando, FL. Northeast Regional Agricultural Engineering Service, Ithaca, NY.

Publications in Print. The following publications have resulted from this NRAC funding:

- Summerfelt, S. T., M. B. Timmons, and B. J. Watten. 2000. Raceway and Tank Culture. In: R. R. Stickney (ed.), *Encyclopedia of Aquaculture*, John Wiley and Sons, Inc., NY.

- Timmons, M.B., S.T. Summerfelt, and B.J. Vinci. 1998. Review of circular tank technology and management. *Aquacultural Engineering* 18(1):51-69.

Manuscripts In Preparation or Review. The following publications resulting from this NRAC funding are in progress:

- Timmons, M.B., S.T. Summerfelt, B.J. Vinci and A.D. Greiner. (In preparation). Effects of tank geometry and flow extraction method on solids removal. *Aquacultural Engineering*. (may be combined with paper listed next)

- Summerfelt, S. T., J. Davidson, M. B. Timmons. (In Preparation). Hydrodynamics in the 'Cornell-type' dual-drain tank. *Aquacultural Engineering.*

PART II. TECHNICAL ANALYSIS AND SUMMARY:

Introduction

Circular tanks make good culture vessels because they can provide a uniform culture environment, can be operated under a wide range of rotational velocities to optimize fish health and condition, and can be used to rapidly concentrate and remove settleable solids. The ability of circular tanks to rapidly flush settleable solids and self clean is a key advantages of the round tank. However, hydrodynamics, tank geometry, and the tank inlet and outlet design all play significant roles in solids flushing and tank mixing within circular tanks. The research reported here describes the influence of the variables on solids fractionation and tank mixing within the new non-proprietary 'Cornell-type' dual-drain circular culture tank.

Circular Tank Hydraulics

Tank hydraulics influence important parameters such as the ability to rapidly flush solids and the amount of water mixing within the tank.

Rotating flow and solids flushing. Circular tanks are operated by injecting water flow along the edge of the tank so that the water spins around the tank center, creating a primary rotating flow. However, as several have summarized (Burrows and Chenoweth, 1955; Larmoyeux et al., 1973; Wheaton, 1977; Skybakmoen, 1989; Tvinnereim and Skybakmoen, 1989; Paul et al., 1991; Goldsmith and Wang, 1993), the no-slip condition that exists between the primary flow and the tank's bottom and sidewalls creates a secondary flow that has an appreciable inward radial flow component at the tank bottom and an outward radial flow at the tank surface (Figure 2.1). This inward radial flow along the bottom of the tank carries settleable solids to the center drain and can create the self-cleaning property so desired in circular tanks. This is the so called "tea-cup effect," which can be simply demonstrated by swirling a tea cup and observing that all the tea leaves are deposited in the bottom center of the cup. It must be noted that circular tanks without proper rotation do not self-clean, which will eliminate rapid solids flushing kinetics and increases the labor required to operate a culture tank. As well, solids removal can depend upon the fish re-suspending the settled materials. This explains in part why fish tanks with low fish biomass do not clean well as tanks with higher fish biomass and how raceways that typically use low water velocities can eventually flush settleable solids.

Largely the design and alignment of the water inlet structure into a culture tank controls its hydrodynamics. Leading work on inlet structure design and alignment was conducted at the SINTEF Norwegian Hydrotechnical Laboratory (Tvinnereim and Skybakmoen, 1989; Skybakmoen, 1989; 1993). Tvinnereim and Skybakmoen (1989) reported that the current velocity in a tank can largely be controlled by varying the inlet impulse force (F_i), which is defined as:

$$F_i = \rho \cdot Q \cdot (V_{orif} - V_{rota}) \qquad \text{(Eq. 1)}$$

where: ρ is the density of water (kg/m^3); Q is the inlet flowrate (m^3/s); v_{orif} is the velocity through the openings in the water inlet structure (orifices or slots) (m/s); and v_{rota} is the rotational velocity in the tank (m/s). The inlet impulse energy largely dissipates as it creates turbulence and rotation in the rotational zone (Figure 2.1). The impulse force, and thus the rotational velocity in the tank, can be regulated by adjusting either the inlet flow rate, the orientation of the inlet flow, or the size and/or number of inlet openings (Tvinnereim and Skybakmoen, 1989; Skybakmoen, 1993).

The rotational velocity in the culture tank should be as uniform as possible from the tank wall to the center and from the surface to the bottom, and it should be swift enough to make the tank self-cleaning. However, it should not be faster than required to exercise the fish. Water velocities of 0.5-2.0 times fish body length per second are optimal for maintaining fish health, muscle tone, and respiration (Losordo and Westers, 1994). Velocities required to drive settleable solids to the tank's center drain should be greater than 15 to 30 cm/s (Burrows and Chenoweth, 1970; Mäkinen et al., 1988; Skybakmoen, 1993). For tilapia, Balarin and Haller (1982) reported an upper current speed of 20-30 cm/s. For salmonids, Timmons and Youngs (1991) provided the following equation to predict safe non-fatiguing water velocities:

$$V_{safe} \leq 5.25/(L)^{0.37} \qquad \text{(Eq. 2)}$$

where: V_{safe} is the maximum design velocity (about 50% of the critical swimming speed) in fish lengths per second and where L is the fish body length in cm. In circular tanks, velocities are reduced somewhat away from the walls, allowing fish to select a variety of water velocities, as compared to raceway designs where velocities are uniform along the channel.

Tank mixing. When flow rotates about a circular tank, a torus-shaped region about the center drain can become an irrotational zone with lower velocities and poor mixing (Figure 2.1). The magnitude of the irrotational zone depends on the force and direction of the flow introduced near the tank wall, the tank's diameter:depth ratio, and the overall rate of flow leaving the center bottom drain. Because the irrotational zone has lower water velocities and does not mix well, it can decrease the effective use of the culture tank by producing short circuiting of flow, by creating localized water quality gradients (especially of concern are reduced oxygen levels), and by providing a quiescent zone where solids can settle and collect. Proper tank design can reduce or eliminate the irrotational zone.

Fortunately, properly designed circular tanks operated with a single bottom drain can provide relatively complete mixing, i.e., the concentration of a dissolved constituent in the water flowing into the tank changes instantaneously to the concentration that exists throughout the tank. Therefore, if adequate mixing can be achieved, all fish within the tank are exposed to the same water quality. Good water quality can be maintained throughout the circular culture tank by proper design and orientation of the water inlet structure and by selecting a water exchange rate so that the limiting water quality parameter does not decrease production when the system reaches carrying capacity. However, there was some concern that effective mixing might be more difficult in the 'Cornell-type' dual-drain culture tanks, because these tanks only flush 5-20% of the tank's hydraulic exchange rate through their center drain. This reduced flow to the tank's center decreases the mass of water exchanged through the center of the tank, which potentially could reduce mixing within the tank. To determine if tank mixing can be effectively achieved within the 'Cornell-type' dual-drain culture tank, dye-tracer studies were conducted as part of this research.

Dual-Drain Culture Tanks

Circular fish culture tanks can be managed as "swirl settlers," settling basins with two effluents, because of their capability to concentrate solids at their bottom and center. Solids that concentrate at the bottom center can be removed in a small flow stream by using a bottom-drawing center drain, while the majority of flow is withdrawn at an elevated drain. As little as 5-20% of total flow leaving the bottom-center drain can effectively carry the majority of settleable solids from the culture tank (e.g., similar to a swirl separator). Use of dual-drain culture tanks has been reported since the 1930s (Cobb and Titcomb, 1930; Surber, 1936). More recently, silo tank used both high and low drains (MacVane, 1979; Slone et al., 1981). Since the late 1980s, many have published on the use of dual-drain tanks for concentrating solids (Mäkinen et al., 1988; Eikebrokk and Ulgenes, 1993; Timmons et al., 1998). There have been at least two recent patents relating to dual-drain tanks:

- Lunde et al. (1997), *Particle trap*, US Patent # 5636595.
- Van Toever (1997), *Water treatment system*. US Patent # 5593574.

The location of the two tank drains have typically been at the center of the tank, which then takes advantage of both the 'tea-cup effect' and the strength of the overall flow when it drains through the tank center. This is the approach has been taken by the manufacturers of the particle trap (marketed by AquaOptima, Norway), Van Toever (1997), and several others, where both the bottom drawing drain and elevated drain are placed at the center of the culture tank. The particle trap (Figure 2.2), for example, endeavors to concentrate the majority of settleable solids into a reduced flow that passes through a gap created between the tank floor and an approach plate incorporated into the particle trap (Lunde et al., 1997).

The 'Cornell-type' dual-drain culture tank (Figure 2.3) differs significantly from the other dual-drain designs, because it only places the bottom drain at the tank's center and removes the majority of flow through an elevated drain located on the tank's sidewall.

Materials and Methods

Settleable solids fractionation and tank mixing were studied within a 3.66 m (12 ft) i.d. x 1.22 m (4 ft) tall circular 'Cornell-type' dual-drain tank at the Freshwater Institute (FI) and a 2 m i.d. x 1 m (3.2 feet) tall (6.5 ft) tank at the Cornell site. Replicated tests were conducted at FI using two hydraulic exchange rates (1 and 2 rearing tank volume exchanges per hour), three diameter to depth ratios (12:1, 6:1, 3:1), three bottom drain flow percentages (5, 10, and 20% of total flow), and in the presence and absence of fish. Similarly at Cornell, replicated tests (minimum of 3) were conducted using two hydraulic exchange rates (3.5 and 7) rearing tank volume exchanges per hour) of total tank flow (center drain is a percentage of total tank flow rate), two diameter to depth ratios (4:1, 2:1), two bottom drain flow percentages (5and 15% of total flow), and at two fish densities (high and low 60 or 120 kg/m^3). The FI used Rainbow trout and were maintained at densities exceeding 60 kg/m^3 and trout were fed 1% body weight per day. Cornell used tilapia in their experiments approximate weight 500 g each and were on full feed. The experimental protocol and the methods described were in compliance with the Animal Welfare Act (9CFR) requirements and were approved by the Freshwater Institute Institutional Animal Care and Use Committee.

Table 2.1 (FI) and Table 2.2 (Cornell) summarize the experimental tests conducted. In the FI tests, some of the trials that we intended to run could not be conducted , because the flow rates through the tank's bottom drain were too low to flush pellets through the drainpipe. Additional tests and trials were conducted, though, to further analyze the fluid dynamics and solids removal characteristics that occur when using the Cornell Double-drain approach. In particular, we used dye tracer tests to determine if tank mixing was adequate during all trials including the impact of fish presence to determine the fish's influence on solids flushing.

Bottom drain flows were set and calibrated using a calibrated bucket and a stop watch. Total flow was measured using a pipe-mounted flow meter; these flows were checked using a stop watch and a larger basin of known volume.

Tank Mixing Tests

At the Freshwater Institute, Rhodamine WT dye was added to the culture tank in a single pulse to determine the effectiveness of tank mixing under the different conditions tested.. The flushing of the dye pulse was monitored by collecting water samples over a period of time. The wave absorption of each water sample was measured using a spectrophotometer set at a wavelength of 555 nm. The absorbance data were plotted for each dye-tracer trial, as illustrated in the sample plot contained in Figure 2.4.

The mean hydraulic retention time (HRT) of the water flowing through the culture tank was estimated using the "mixing-cup" method described on page 63.3 of Levenspiel's Chemical Reactor Omni Book (1989), as follows:

$$\text{Measured mean residence time (min)} = \frac{\sum_{i=1}^{n} t_i \cdot C_i \cdot \Delta t_i}{\sum_{i=1}^{n} C_i \cdot \Delta t_i} \qquad \text{(Eq. 3)}$$

where: C_i is the absorbance of sample i, t_i is the length of time the sample i was collected after the dye-tracer was input into the tank, and Δt_i is the interval between adjacent samples when sample i was collected. The 'mixing-cup' method accounts for unequal sample intervals within the data.

The ideal mean residence time was also calculated using the water volume in the tank (V) and the water flowrate through the tank (Q):

$$\text{Ideal mean residence time (min)} = \frac{\text{water volume in vessel (L)}}{\text{water flow through vessel (L/min)}}$$

$$= \frac{V}{Q}$$

(Eq. 4)

Tank turnover efficiencies were estimated from the ratio of the two residence times found above:

$$\text{turnover efficiency} = \frac{\text{measured mean residence time (min)}}{\text{ideal mean residence time (min)}}$$

(Eq. 5)

If mixing within the tank is perfect, the tank turnover efficiencies equal 1.0. Turnover efficiencies of less than 1.0 indicate less than perfect mixing and that some water short circuits through the culture tank. Turnover efficiencies greater than 1.0 are an indication of problems with the precision of water flow rate or tank volume measurements, or inconsistencies within the samples taken during the dye-tracer test.

Solids Flushing Tests

Pulses of sinking PVC cylindrical pellets (each about 3 mm in length by 3 mm o.d.) were added to quantify solids flushing kinetics and the relative strength of the radial flow. The plastic pellets had a specific gravity of 1.05 (Michael Timmons, Cornell University, personal communication), similar to the specific gravity reported for trout fecal matter: 1.005 (Robertson, 1992), 1.13-1.20 (Timmons and Youngs, 1991), 1.19 (Chen et al., 1993). The plastic pellets also exhibited a settling velocity of 3.8 cm/s, which was similar to the settling velocity reported for fecal matter 1.7-4.3 cm/s (Warrer-Hansen, 1982). Feed pellets tested in this study exhibited a much more rapid settling velocity (e.g., 14 cm/s) than the plastic beads. However, others have reported similar feed settling velocities of 15-33 cm/s (Juell, 1991).

In both studies (Cornell and FI), one thousand grams of dry pellets were weighed out, wetted in a bucket to remove air bubbles from the pellets, and placed into the tank water in a pulse. The plastic pellets settled fairly rapidly and were transported by radial flow to the bottom center of tank towards the center drain. The plastic pellets were then collected from the bottom drain discharge at specific time intervals. Baskets containing 1-mm mesh stainless steel screen were used to capture the beads from the flow during each sampling interval. Following collection, the beads were dried oven dried and weighed. A minimum of three pulsed-pellet tests were run for each set of conditions.

An unsteady-state mass balance was developed to quantify pellet flushing, assuming zero pellet inflow, reaction, or accumulation:

Loss = ~~Inflow~~ – Outflow – ~~Reaction~~ – ~~Accumulation~~

(Eq. 6)

The outflow term in the mass balance was broken into a component representing simple mass action of flow to the bottom drain, and a component representing pellet enrichment at the bottom drain due to a combination of sedimentation and radial flow (assuming that the pellet outflow at the tank's sidewall is negligible); this was done to distinguish between the two different mechanisms transporting pellets to the bottom center drain:

Loss = – Outflow (mass action) – Outflow (enrichment)

(Eq. 7)

Or more specifically,

$$V \cdot \frac{dC}{dt} = -Q_{out,\,b} \cdot C_{out,\,b} - k \cdot C_{out,\,b} \cdot V$$

$$= V \cdot \{-Q/V + k) \cdot C_{out,\,b}\}$$

(Eq. 8)

where: k is a 1st order rate constant characterizing bead enrichment at the bottom-center drain and $Q_{out,b}$ and $C_{out,b}$ are the flowrate and concentration of pellets flushed through the bottom center drain at a given time.

Integration provides an equation that can be used to model pellet flushing through the bottom drain in real time:

$$C_{out,b}\ (@t) = C_{out,b}\ (@t = 0) \cdot e^{\{-(Q/V+k)t\}}$$

(Eq. 9)

Note that the flushing of a homogeneously distributed dye pulse is only due to mass action (i.e., the culture tank exchange rate Q/V):

$$C\ (@t) = C\ (@t = 0) \cdot e^{-(Q/V)\cdot t}$$

(Eq. 10)

Therefore, the k-value (1st order enrichment constant) increases the rate of solids flushing relative to the culture tank exchange rate.

After manipulation of Eq. 9, the k-value for each pellet flushing test was calculated from the slope of the line produced by plotting the pellet flushing data (Figure 2.5) after manipulation to the following form:

$$\text{y-axis} = -\ln[\text{fraction solids remaining}] \qquad \text{(Eq. 11)}$$

$$\text{x-axis} = t \qquad \text{(Eq. 12)}$$

$$\text{slope of the linear regression line} = (Q/V + k) \qquad \text{(Eq. 13)}$$

A sample pellet flushing test is shown in Figure 2.5. Note that not all the data fits the assumption that pellet enrichment at the bottom center drain due to settling and radial flow could be approximated by 1st order kinetics. In most tests, effective pellet flushing occurred and this would result in very little (e.g. less than 5%) of the pellets not behaving according to the 1st order kinetic equation. The Results summarize for each trial the percentage of pellets (data) that was excluded in determining the k value for each experimental condition.

Results and Discussion

Freshwater Institute: Solids Partitioning Between Side-wall and Bottom-Center Drains

In the Freshwater Institute (FI) trials, less than 5% of the sinking pellets were flushed through the sidewall drain during all trials (Figure 2.6). However, larger fractions of pellets were flushed through the sidewall drain when fish were present (e.g., < 4.3%) than during trials conducted in the absence of fish (e.g., < 1.4% (Figure 2.6). Increasing the culture tank exchange rate from 1 ex/hr to 2 ex/hr also increased the fraction of pellets flushed through the sidewall drain from < 1.4% to mostly < 4.3% (Figure 2.7).

The k-values estimated from the pellet-tracer tests are an indication of the rate that pellets can be flushed from the bottom-center drain and also of the relative strength of the radial flow. When fish were present, the rate that pellets were flushed through the bottom-center drain was greater at 2 ex/hr than at 1 ex/hr (Figure 2.8) and at the smaller diameter:depth ratios (Figure 2.9). All the trials at 2 ex/hr and diameter:depth ratios of 3.1:1 and 6:1 produced strong radial flows, rapid solids flushing, and exhibited no problems with solids flushing (Figure 2.9).

Key Observation. A very important observation was that the settleable solids frequently deposited about the tank's bottom-center drain (Figure 2.10) during most trials at 1 ex/hr, but only at the diameter:depth ratio of 12:1 during trials at 2 ex/hr (Figures 2.8 and 2.9).. During these trials, the radial flow transported the settleable solids to the center portion of the tank, but water velocities were so low in the middle of the tank that a good portion of these solids settled within a torus-shaped region about the center drain. Fortunately, this accumulation of settled solids were usually sufficiently near to the center drain that pulling the external stand-pipe regulating the bottom-center drain flow, even for an interval of < 1 min, was sufficient to flush the accumulated solids. The presence of fish improved the rate that pellets were flushed through the bottom-center drain (i.e., the K-values) for a given diameter:depth, underflow percentage, and overall tank exchange rate (Figure 2.11).

The relative importance of the two pellet flushing mechanisms, i.e., mass action (i.e., Q/V) versus enrichment at bottom-center drain (k), was illustrated by calculating the percentage of pellet flushing due to enrichment alone:

$$\%\ \text{flushing due to enrichment} = \frac{k}{k + Q/V} \cdot 100 \qquad \text{(Eq. 14)}$$

The radial flow mechanism played a much larger role than the mass transport mechanism in the transport of pellets to the bottom-center drain during the trials at 2 ex/hr and diameter:depth ratios of 3.1:1 and 6:1 and during the 1 ex/hr trials at diameter:depth ratios of 3.1:1 (Table 2.3). Pellets were not flushed effectively during the remainder of the trials, so the k-values and the enrichment percentage shown in Table 2.3 could not be calculated under these conditions.

Cornell Results and Interpretation of Results

Similar findings were found in the Cornell studies (see Table 2.4). Tables 2.3-2.7 summarize: k values, enrichment due to center drain flow (k/(Q/V+k), average dead time and percent of data not conforming to first order kinetics to estimate "k". Note that in the Cornell results that striking similarity occurs in the phenomena. Quite clearly, as the tank depth increases (or DDR decreases), the enrichment factor is much higher for the "deeper" tanks. Similarly, the k values for the deep tank study are roughly twice the k values for the shallow tanks (0.14 versus 0.05). This also indicates that previous recommendations (Larmoyeux et al., 1973) on recommended diameter to depth ratios to be between 5 and 10-- should be revisited according to these results. It appears that DDR less than 5 and perhaps as low as 2 may be preferred to "shallower" tanks based upon the increase in enrichment as characterized by the k value and k/(Q/V + k). This is very important because it impacts positively the quantity of fish that can be maintained as a standing biomass per unit floor area. Fish behavioral characteristics must also be considered, e.g. flounder that need floor space versus say tilapia that distribute well vertically in the water column.

Tank Dead-Time Estimates

The pellet-pulse data when plotted according to the –LN(fraction of solids remaining) versus time (Figure 2.5) also provides a graphical estimate of the time required for the beads to travel from the tank's surface to the bottom center drain, i.e., the dead time (t_0) for solids flushing from the tank. The x-intercept of this data provides the estimate of the tank's dead time. The dead times for the different bead-flushing trials are reported in Table 2.6.

Additionally, not all of the data was included in the linear regression of the bead-pulse data as plotted according to the –LN(fraction of solids remaining) versus time, as in the example shown in Figure 2.5. This data was excluded because it did not fit the 1st order kinetics assumption for solids enrichment at the bottom-center drain (Table 2.7). We think that when large portions of the pellets did not exhibit enrichment at the center drain according to 1st order kinetics, it was due to insufficient velocity in the rotational flow, i.e. the actual water velocity starting from the outside wall. Under these low velocity conditions, the pellets did not flush rapidly because they settled on the tank floor just before reaching the tank's center drain (Figure 2.10 and 2.11). Velocities at the outside walls appear to require velocities of at least 15 cm/s (0.5 ft/s) to promote solids departure from the center drain.

Tank Mixing

The culture tank exhibited good mixing characteristics during all trials with fish present, as illustrated by tank turnover efficiencies plotted in Figure 2.12. However, mixing was often most complete during the 2 ex/hr trials than at the 1 ex/hr trials (Figure 2.8).

Settleable Solids Fractionation and Waste Management

Total suspended solids (TSS) concentrations were measured during all trials where fish were present. TSS samples were collected on the tank's inlet flow, both tank outlet flows, and the tank's bottom-center drain outlet flow after it has passed through a microscreen filter. There was considerable variability found within the TSS data, which is fairly routine with these samples since the concentrations are very low (a few mg/L) and presence of a single particle can impact a particular sample also be several mg/L. Therefore, the TSS data that was collected during all of the trials was combined according to its sampling location (Table 2.8). This data indicates that the flow discharged from the 'Cornell-type' tank's bottom-center drain contained TSS concentrations (i.e., 19.6 ± 3.6 mg/L) that were more than 10-times greater than the TSS concentration discharged from the side wall drain (i.e., 1.5 ± 0.2 mg/L). For these trials, the concentration of TSS discharged from the sidewall drain was sufficiently low that it would not require further solids treatment in order to pass even many of the more stringent discharge limits imposed by environmental regulatory agencies. Amazingly, the sidewall drain, which is considered to represent the TSS of the tank water column, contained only about 1.0 mg/L more TSS than the fresh-water makeup that was introduced into the tank. On the other hand, the concentrated and relatively small flow discharged from the bottom-center drain would definitely require treatment before discharge. However, this flow was treated effectively using a microscreen filter where, where on average, greater than 80% of the TSS discharged from the circular culture tank's bottom-center drain was captured.

The flow discharged from the 'Cornell-type' dual-drain tank's bottom-center drain sweeps the fecal matter and waste feed from the tank in only a matter of minutes. After leaving the culture tank, this more concentrated waste flows into a microscreen filter where much of the particulate matter can be removed within another several minutes. This rapid removal of particulate wastes from the water prevents the particulate waste from degrading into smaller pieces, which are harder to remove and more readily leach nutrients into the water column. Therefore, use of the 'Cornell-type' dual-drain culture tank in conjunction with a microscreen filter is an extremely effective method of capturing particulate wastes.

Conclusions

The 'Cornell-type' dual-drain culture tank addresses two very real industry needs: it can provide improved water quality within the culture environment, and improved waste capture before the water is discharged.

Waste management is a major problem facing aquaculture. State and private hatcheries have been required to reduce the quantities of waste being discharged from their systems (Ewart et al. 1995). Limits are often placed on concentrations or total mass of solids, biochemical oxygen demand, total phosphorus, and total nitrogen in the aquaculture discharge. Because roughly 80% of the total phosphorus in an aquacultural effluent is associated with solids, increased particulate removal reduces effluent levels of solids, BOD, and total phosphorus. The cost of waste removal from discharge waters is one of the major costs of production other than the raw inputs of feed and fingerlings. Many current intensive systems face closure or severe reduction in allowable feeding rates by regulatory agencies unless waste discharges are reduced.

Profitability of intensive tank production systems is also highly impacted by water quality, which in turn impacts the rate of feed assimilation by fish. Water quality becomes increasingly difficult to maintain as the rate of feeding increases. However, gross returns are directly related to fish biomass production and production rates are highly related to feedings rates. Control of suspended solids in the fish water column is one of the primary controlling factors of how much feed can be fed per day, and in turn, feeding rates largely determine the overall economics of intensive aquaculture systems, whether they are flow-through systems or recirculating systems. For aquaculture to remain viable, it is critical that cost effective methods are developed for the removal of suspended solids.

Because the costs of solids removal in aquaculture are controlled more by the volume of flow treated than by solids concentration, system designers are looking for simple means to concentrate solids into smaller volumes. Removing solids using a dual-drain system has the potential to improve the economics of solids removal both within the fish water column and from the effluents of flow-through and water-reuse systems. The Cornell Double-drain technique works because rotational flow in circular tanks concentrates solids at their bottom and center. When a circular fish-culture tank is converted into a “swirl” separator, the concentrated solids are removed in a relatively small flow stream leaving the bottom-drawing center drain in a culture tank; however, the majority of the flow (relatively free of settleable solids) leaving the tank is withdrawn through a fish-excluding port located part-way up the tank sidewall as in the Cornell Double-drain system. Once the solids are concentrated into a much smaller discharge, this reduced flow can be treated more economically with a device such as a microscreen filter or settling basin.

References

Balarin, J. D., Haller, R. D., 1982. The intensive culture of tilapia in tanks, raceways, and cages. In: J. F. Muir, R. J. Roberts (Eds.), *Recent Advances in Aquaculture*. Westview Press, Boulder, CO, pp. 265-356.

Burrows, R., Chenoweth, H., 1955. Evaluation of Three Types of Fish Rearing Ponds. Research Report 39, U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C., 29 pp.

Burrows, R., Chenoweth, H., 1970. The rectangular circulating rearing pond. *Prog. Fish-Cult.* 32, 67-80.

Chen, S., Timmons, M.B., Aneshansley, D.J. and J.J. Bisogni, 1993. Suspended solids characteristics from recirculating aquacultural systems and design implications. *Aquaculture* 112:143-155.

Cobb, W. W., Titcomb, J. W., 1930. A circular pond with central outlet for rearing fry and fingerlings of the salmonidae. *Trans. Am. Fish. Soc.* 60, 121-123.

Eikebrokk, B., Ulgenes, Y., 1993. Characterization of treated effluents from land based fish farms. In: H. Keinertsen, L. A. Dahle, L. Jorgensen, K. Tvinnereim (Eds.), Fish Farming Technology. Proceedings of First International Conference, August 9-12, 1993, Trondheim, Norway. Balkema, Rotterdam, pp. 361-366.

Ewart, J., J. A. Hankins, and D.Bullock. 1995. *State Policies for Aquaculture Effluents and Solid Wastes in the Northeast Region.* Northeast Regional Aquaculture Center, University of Massachusetts, Dartmouth, MA.

Goldsmith, D. L., Wang, J.-K., 1993. Hydromechanics of settled solids collection using rotating flow. In: J.-K. Wang (Ed.), Techniques for Modern Aquaculture (Proceedings). June 21-23, 1993, Spokane, Washington. American Society of Agricultural Engineers, Saint Joseph, MI, pp. 467-480.

Juell, J. E., 1991. Hydroacoustic detection of food waste--A method to estimate maximum food intake of fish populations in sea cages. *Aquacult. Eng.* 10, 207-217.

Larmoyeux, J. D., Piper, R. G., Chenoweth, H. H., 1973. Evaluation of circular tanks for salmonid production. Prog. *Fish-Cult.,* 35, 122-131.

Levenspiel, O. 1989. The Chemical Reactor Omnibook. Oregon State University Book Stores, Inc., Corvalis, OR.

Losordo, T. M., Westers, H., 1994. System carrying capacity and flow estimation. In: M. B. Timmons, T. M. Losordo (Eds.), Aquaculture Water Systems: Engineering Design and Management. Elsevier, NY, pp. 9-60.

Lunde, T., Skybakmoen, S., Schei, I., 1997. Particle trap. US Patent 5,636,595.

MacVane, T. 1979. Fish culture tank. US Patent 4,141,318.

Mäkinen, T., Lindgren, S., Eskelinen, P. 1988. Sieving as an effluent treatment method for aquaculture. *Aquacult. Eng*. 7, 367-377.

Mudrak, V. A. 1981. Guidelines for economical commercial fish hatchery wastewater treatment systems. Pages 174-182 In L. J. Allen and E. C. Kinney (eds.), *Proceedings of the Bio-engineering Symposium for Fish Culture*. American Fisheries Society, Fish Culture Section, Bethesda, MD.

Paul, T. C., Sayal, S. K., Sakhuja, V. S., Dhillon, G. S., 1991. Vortex-settling basin design considerations. *J. Hydraul. Eng.* 117, 172-189.

Robertson, W. D. 1992. *Assessment of filtration and sedimentation systems for total phosphorus removal at the Lake Utopia Fish Culture Station.* Canadian Fish Culture Operations, Aquaculture Division, Connors Bros., Limited, Blacks Harbour, New Brunswick, Canada.

Skybakmoen, S., 1989. Impact of water hydraulics on water quality in fish rearing units. In: Conference 3--Water Treatment and Quality. Proceedings of AquaNor 89, August 11-16, 1989. AquaNor, Trondheim, Norway, pp. 17-21.

Skybakmoen, S., 1993. Fish Rearing Tanks. Aquaculture Series Brochure, AGA AB, Lidingö, Sweden, 12 pp.

Slone, W. J., Jester, D. B., Turner, P. R., 1981. A closed vertical raceway fish culture system containing clinoptilolite as an ammonia stripper. In: L. J. Allen, E. C. Kinney (Eds.), Proceedings of the Bio-engineering Symposium for Fish Culture (FCS Pub. 1). Symposium held October 16-18, 1979. Traverse City, Michigan. American Fisheries Society, Bethesda, MD, pp. 104-115.

Surber, E. W., 1936. Circular rearing pools for trout and bass. *Prog. Fish-Cult.,* 21, 1-14.

Timmons, M. B., Youngs, W. D., 1991. Considerations on the design of raceways. In: P. Giovannini (Session Chairman), Aquaculture Systems Engineering. Proceedings of World Aquaculture Society and American Society of Agricultural Engineers, June 16-20, 1991, San Juan, Puerto Rico (ASAE Publication 02-91), American Society of Agricultural Engineers, St. Joseph, MI**.**

Timmons, M.B., S.T. Summerfelt, and B.J. Vinci. 1998. Review of circular tank technology and management. *Aquacultural Engineering* 18(1):51-69.

Tvinnereim, K., Skybakmoen, S., 1989. Water exchange and self-cleaning in fish rearing tanks. In: N. De Pauw, E. Jaspers, H. Ackefors, N. Wilkens (Eds.), Aquaculture: A Biotechnology in Progress. European Aquaculture Society, Bredena, Belgium, pp. 1041-1047.

Van Toever, W., 1997. Water Treatment System Particularly for Use in Aquaculture. U.S. Patent 5,593,574.

Warren-Hansen, I. 1982. Methods of treatment of waste water from trout farming. Pages 113-121 In J. Alabaster (ed.), EIFAC Technical Paper No. 41. Report of the EIFAC Workshop on Fish-Farm Effluents, Silkeborg, Denmark, 26-28 May, 1981, FAO Rome.

Wheaton, F. W., 1977. Aquacultural Engineering. Robert E. Krieger Publishing Co., Malabar, FL, 708 pp.