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Solids removal from a coldwater recirculating system—comparison of a swirl separator and a radial-flow settler

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Abstract

Solids removal across two settling devices, i.e., a swirl separator and a radial-flow settler, and across a microscreen drum filter was evaluated in a fully recirculating system containing a single 150 m^3 'Cornell-type' dual-drain tank during the production of food-size Arctic char and rainbow trout. The flow through the culture tank was 4500–4800 L/min. Approximately 92–93% of the system flow exited through the Cornell-type sidewall drain. The remaining 7–8% of the flow, approximately 340 L/min, exited through a bottom–center drain and an external standpipe and then to the settling tank. The surface-loading rate applied to both settling tank designs was 0.0031 m^3/s per square meter (4.6 gpm/ft^2) of settling area. The swirl separator and the radial-flow settler were evaluated over a range of feeding rates to evaluate the relationship between inlet TSS concentration and TSS removal efficiency. There was a highly significant difference ($P < 0.001$) in mean TSS removal efficiency of the swirl separator and radial-flow settler, (±S.E.) $37.1 \pm 3.3\%$ and $77.9 \pm 1.6\%$, respectively. Also, TSS removal efficiency of the radial-flow settler was less variable than removal efficiency of the swirl separator. The trend in TSS removal efficiency was consistent over a broad range of inlet TSS concentrations to the separator. A mass balance indicates that the swirl separator only removed approximately 23% of the total mass of TSS removed from this recirculating system. However, when the radial-flow settler was operated in the same recirculating system, it accounted for approximately 48% of the mass of TSS removed from the system daily. The mass balance calculations also indicate that the microscreen drum filter accounted for approximately 40–45% of the mass of TSS removed daily from the recirculating system when using either settling device. In either case, these results

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indicate that drum filter treatment of the entire recirculating flow played an important role in preventing elevated TSS concentrations from accumulating within a recirculating system.

Keywords: Swirl separator; Radial-flow settler; Recirculating system; Waste capture; Solids flushing; Water reuse

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1. Introduction

Rapid and effective solids removal can positively affect the health of salmonid species in water recirculating systems (Bullock et al., 1994, 1997). Accumulation of solids within aquaculture tanks and systems can promote an environment that harbors fish pathogens. In addition, solids that are not rapidly removed can break down into smaller particles that leach nutrients, degrade water quality, and exert a biological oxygen demand that also increases dissolved carbon dioxide levels. These smaller suspended solids can cause gill irritation, which can lead to reduced immune system efficiency, and ultimately disease outbreak (Stickney, 1979; Wickens, 1980). Failure to effectively remove solids from aquaculture systems can also have adverse effects on system components. For example, excess solids can cause plugging within aeration columns, screens, and spray bar and spray nozzle orifices, which could ultimately result in system failure.

Many of the recently installed recirculating systems that are used for Arctic char, rainbow trout, or salmon smolt production in North America use dual-drain culture tanks (Wilton and Boschman, 1998; Summerfelt et al., 2004a,b). Dual-drain culture tanks are used to rapidly fractionate and flush the majority of settleable solids from the culture tank's bottom–center drain within a comparatively low flow, typically 5–20% of the total flow (Mäkinen et al., 1988; Eikebrokk and Ulgenes, 1993, 1998; Twarowska et al., 1997; Timmons et al., 1998; Losordo et al., 2000; Davidson and Summerfelt, 2004). Relatively small swirl separators (i.e., <1–2 m diameter) are then used to capture settleable solids that have been concentrated within the culture tank's bottom drain flow (Eikebrokk and Ulgenes, 1993, 1998; Twarowska et al., 1997; Losordo et al., 2000; Summerfelt et al., 2004a). In recirculating systems designed with multiple tanks, one swirl separator is usually associated with each culture tank. This design reduces the distance that the solids laden water must travel to reach the settling unit, which reduces the opportunity for solids degradation within the piping.

Swirl separators, also known as tea cup settlers or hydrocyclones, operate by injecting water tangentially at the outer radius of a conical tank, causing the water to spin around the tank's center axis. The primary rotation inside the tank creates a secondary radial flow towards the center of the conical tank and the inertial forces created are used to improve solids capture (Paul et al., 1991; Andoh, 1998). Swirl separators have traditionally been used to treat wastewater flows that contain particles of high specific gravity, e.g., sand and grit that have a specific gravity 2.65 times that of water (Paul et al., 1991; Andoh, 1998). Because aquaculture solids can have a specific gravity of 1.005–1.20 (Warren-Hansen, 1982; Wong and Piedrahita, 2000), which is only slightly greater than water, concentrating these solids within settling devices is not always guaranteed and performance is dependent on maintaining proper hydraulics in the settling device (IDEQ, 1998; Henderson and

Bromage, 1988). Veerapen et al. (in press) report that removal of aquaculture solids across a swirl separator is mainly gravity driven and is relatively independent of inertial forces. Veerapen et al. (in press) found that the surface-loading rate on the swirl separator was the most important parameter in sizing a swirl separator to treat a waste with a given settling velocity. They also report that solids capture can be improved when the inlet flow produces lower water rotational velocities, when the structure of the overflow is moved away from the center of the swirl separator, and when the area of the overflow outlet is increased to reduce outlet flow velocities.

Because aquaculture solids can have a low specific gravity, solids can remain suspended in the overtopping flows that exit swirl separators and dual-drain tanks. Therefore, the overtopping flows exiting swirl separators and dual-drain culture tanks are often passed through a secondary filtration device such as a drum filter for more complete solids removal before the treated water is recirculated back to the culture tanks (Twarowska et al., 1997; Eikebrokk and Ulgenes, 1998; Losordo et al., 2000; Summerfelt et al., 2004a).

Radial-flow settling units, also called circular center-feed sedimentation basins, are the most common settling tank design used in municipal wastewater treatment plants (Metcalf and Eddy Inc., 1991). A radial-flow settler is only similar to a swirl separator in that they are both cylindrical settling tanks with effluent launders located around the top perimeter of the vessels and sometimes with cone bottoms. However, radial-flow settlers have completely different flow hydraulics from swirl separators. A radial-flow settler introduces water into the center of the vessel, inside a ‘turbulence-dampening’ cylinder, and the water injected into the center of the tank then flows outward (in the vessel’s radial direction) to the overflow collection launder that surrounds the perimeter of the settler. Radial flow away from the center of the circular tank produces a progressively decreasing water velocity along the settling path. In addition, the circumference of the circular vessels produces a substantial outlet weir length, which can provide a relatively low weir-loading rate. According to Metcalf and Eddy Inc. (1991), the design of the flow injection point within the center of the radial-flow settler is critical to dampen the turbulence created by the flow injection at the center of the tank. Therefore, the turbulence-dampening cylinder, located at the center of the circular settling tank, should be designed with a minimum diameter that is 25% of the tank diameter and should be located well above the maximum depth of sludge to minimize resuspension of the captured solids (Metcalf and Eddy Inc., 1991). Water Pollution Control Federation (1985) provides additional details on inlet design for radial-flow settling units.

The study reported here is based on the hypothesis that flow hydraulics created within a radial-flow settler would create better settleable solids removal than those created within a swirl separator.

Ideally, the settling unit that is used to treat solids concentrated within the culture tank’s bottom–center drain flow would be capable of capturing the majority of the settleable solids entering the settling unit. Research was needed to determine the settleable solids capture efficiency of radial-flow settlers and swirl separators.

The objective of the research presented in this paper was to evaluate solids removal efficiencies within a commercial-scale recirculating system used for salmonid production. This paper presents the changes in total suspended solids (TSS) concentration and mass across the recirculating system’s microscreen drum filter, used to treat the entire recirculating flow, and a solids settling device that was used to remove solids contained within the bottom–center drain exiting the ‘Cornell-type’ dual-drain culture tank. This research investigated the performance of two settling devices installed to treat the Cornell-type dual-drain culture tank’s bottom–center drain flow, i.e., a swirl separator and a radial-flow settler. The study was designed to evaluate solids removal across the drum filter and the two solids settling devices when they were operated at the same hydraulic loading rate and at various fish feeding rates.

2. Materials and methods

This study tested for fish waste removal within a full-scale settling unit and a full-scale microscreen drum filter placed within a commercial-scale water recirculating system used for growout of food-size Arctic char (1.3 kg at harvest) and then for growout of food-size rainbow trout (0.7 kg at harvest). Although simple, the approach used in this study avoids complications with similitude that must be overcome when estimating full-scale settling basin performance from tests conducted in relatively small-scale test units. Because this study evaluated removal of solids directly as they are discharged from the bottom–center drain of a fish culture tank, this approach also avoided need for extrapolating settleable solids capture efficiency from studies using an artificial waste that mimics the size and settling velocity of fish fecal matter.

2.1. Recirculating system

The recirculating system, which has been described elsewhere (Summerfelt et al., 2004a), used two 5-HP centrifugal pumps to recirculate approximately 4500–4800 L/min of water. Water was pumped through a Cyclo Bio^{TM} fluidized-sand biofilter. The water exiting the top of the Cyclo Bio^{TM} biofilter flowed by gravity through a forced-ventilation gas-stripping column, then through a low head oxygenation (LHO) unit, and then through a UV irradiation unit (Fig. 1). The water flowing out of the UV irradiation channel unit was then piped by gravity into the system’s 150-m^3 Cornell-type dual-drain culture tank. Approximately 92–93% of the system flow exited the culture tank through the tank’s sidewall drain and then passed through a microscreen drum filter installed with 90 μm sieve panels before flowing into a pump sump (Fig. 1). The remaining 7–8% of the flow, approximately 340 L/min, exited the culture tank through its bottom–center drain and an external standpipe and then flowed by gravity through a settling device (Fig. 1), originally designed as a swirl separator. Treated water leaving the settling device was divided into two flows: the majority of water was discharged from the system and replaced with makeup water, but a small portion of the water exiting the settling unit was directed back to the drum filter (Fig. 1) during the testing of the radial-flow settler. The flow split leaving the settling unit was dependent on the desired makeup water flow rate and was adjusted accordingly.

In order to determine the influence of TSS inlet concentration on solids capture efficiency, solids removal characteristics were evaluated across the microscreen drum filter and across each settling unit when the recirculating system was operated during periods of

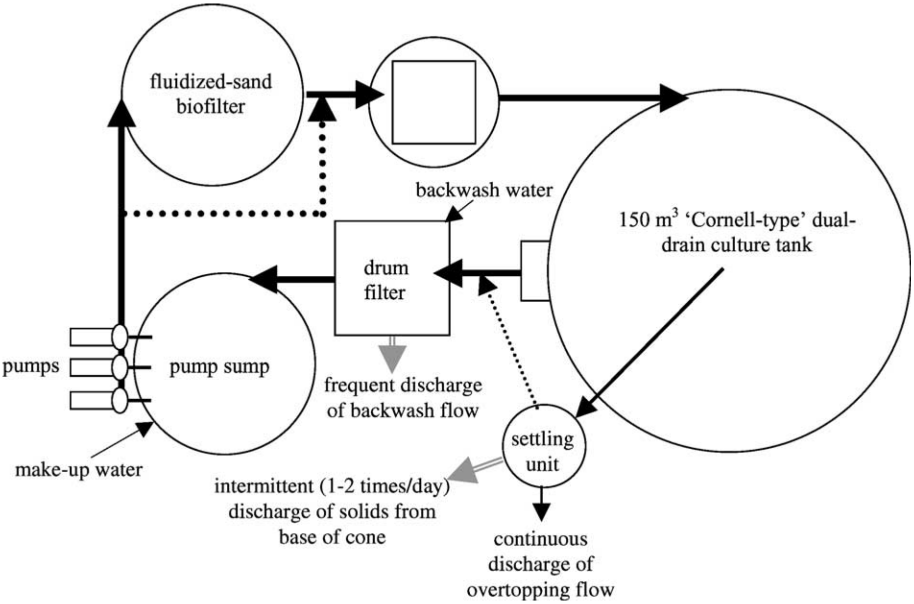

Fig. 1. Process flow drawing of the recirculating salmonid growout system located at the Freshwater Institute (Shepherdstown, WV).

relatively low feeding and relatively high feeding. Solids removal at the low feeding rate occurred when the system was initially stocked at an average density of 25 kg/m^3 and when mean fish feeding rates averaged only 52 and 66 kg/day for the system when stocked with Arctic char and rainbow trout, respectively. Additional TSS data was collected at higher fish densities (i.e., approximately 96 and 74 kg/m^3 for the system when stocked with Arctic char and rainbow trout, respectively), and higher fish feeding rates (i.e., approximately 111 and 123 kg feed per day for the system when stocked with Arctic char and rainbow trout, respectively) had been achieved. The fish culture system was maintained in a room operated with a 24 h continuous photoperiod. In order to ensure a nearly continuous waste production rate, fish were fed equal portions eight times daily, i.e., one feeding every 3 h, using PLC controlled mechanical feeders.

2.2. Settling units

Solids separation from the bottom drain effluent was evaluated at full-scale using two settling tank designs: a swirl separator (Fig. 2) and a radial-flow settler (Fig. 3). A single settling tank was modified to evaluate both designs. The cylindrical settling tank was 1.52 m (5.0 ft) diameter by 2.1 m (6.9 ft) tall and contained a V-notch weir and effluent launder that circumscribed the top perimeter of the tank (Figs. 2 and 3). The settling tank also contained a 60° cone bottom with an overall height of 1.30 m (4.25 ft) and a 7.5 cm (3 in.) diameter drain at its base (Figs. 2 and 3). The V-notch weir set the water level within the settling tank at approximately 1.77 m (5.79 ft) above the base of the cone. In the first

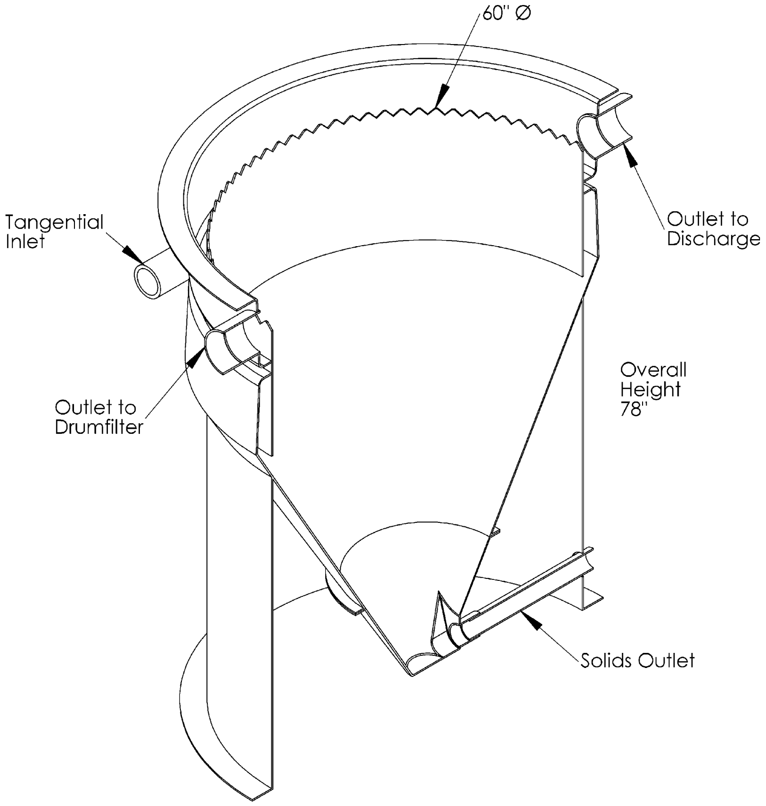

Fig. 2. Line drawing of the swirl separator that was tested. Drawing courtesy of Marine Biotech Inc. (Beverly, MA).

trial, the tank was operated as a swirl separator by introducing the water flow through a 10 cm (4 in.) diameter tangential inlet that was located with its centerline approximately 0.38 m (1.25 ft) below the top of the V-notch weir (Fig. 2). To convert the swirl separator to a radial-flow settler, the settling tank was modified by first capping off the tangential inlet and then running a new 10 cm (4 in.) diameter influent pipe to the center of the tank, where it turned up at a 90° angle and spilled out of the pipe just below the water surface (Fig. 3). Also, a 0.61 m (2 ft) diameter by 0.61 m (2 ft) tall fiberglass cylinder was installed around the influent pipe (Fig. 3) to dampen water turbulence at the point of water injection. By introducing flow at the water surface at the center of the turbulence-dampening cylinder, water was first forced to flow downward—below the turbulence-dampening cylinder—as it flowed radially to the V-notch weir at the perimeter of the settling tank. These modifications changed the settling device from a swirl separator to a radial-flow settler.

No flow was discharged from the bottom of the settling tank cone during normal operation, for either the swirl separator or radial-flow settler trials. Solids were manually flushed from each of the settling basins in pulse once or twice daily. The settling units were completely drained and sprayed with wash water once per week. System flow rates

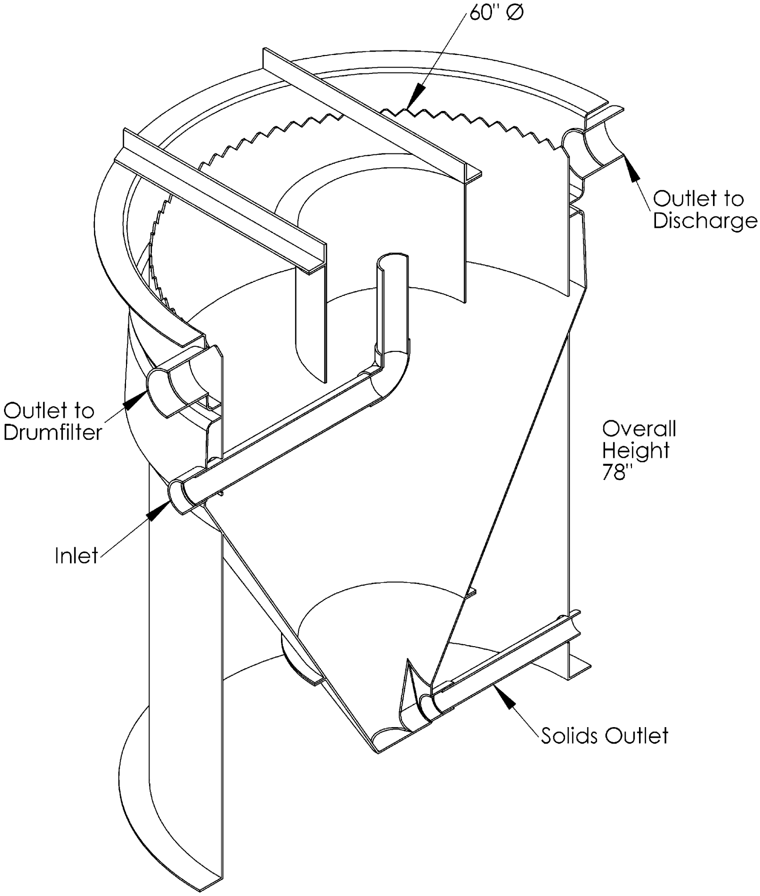

Fig. 3. Line drawing of the radial-flow settler that was tested. Drawing courtesy of Marine Biotech Inc. (Beverly, MA).

were measured using the Transport Model PT868 ultrasonic flow meter (Panametrics, Waltham, MA).

2.3. Solids analysis

To evaluate the effectiveness of solids removal, water samples for TSS analysis were collected one to two times per week from the culture tank's inlet flow, side-wall outlet flow, and bottom–center drain outlet flow, as well as from the drum filter outlet flow, the settling unit outlet flow, and the makeup flow entering the system. A total of 53 sets of samples were collected intermittently over a period of several years, during periods of both high and low feeding levels, to ensure that sampling provided representative average TSS concentrations. TSS concentrations were analyzed using American Public

Health Association (APHA, 1998) method 2540 D, which measures the residue of solids captured on a weighed standard glass-fiber filter that has been dried to a constant weight at 103–105 °C.

TSS removal efficiency across the microscreen drum filter and across the settling unit were calculated from the unit's inlet and outlet concentrations on each day that data was collected, and then the mean TSS removal efficiency (±standard error, S.E.) from all data sets was calculated (Table 1). Alternatively, if the mean inlet and outlet concentrations tabulated in Table 1 had been used to calculate removal efficiency, this

Table 1
Mean (±S.E.) TSS concentrations, TSS removal efficiencies, water flow and mass flows, and fish feeding rates on days when the swirl separator and radial-flow settler were evaluated

Concentration of TSS at different locations	Swirl separator system	Radial-flow settler system
Culture tank inlet TSS, mg/L	2.4 ± 0.5	2.7 ± 0.3
Makeup water TSS, mg/L	0.4 ± 0.1	0.4 ± 0.1
Bottom drain outlet = settling device inlet TSS, mg/L	16.5 ± 1.3**	27.7 ± 2.6**
Side drain outlet ≅ drum filter inlet TSS, mg/L	3.2 ± 0.3	4.5 ± 0.6
Settling unit outlet TSS, mg/L	9.6 ± 0.5	6.4 ± 0.4
Drum filter outlet TSS, mg/L	2.2 ± 0.2	3.1 ± 0.4
Number of data points included	24	22
Mean solids removal efficiency or fractionation (mean removal efficiency was calculated from all daily removal efficiency)		
TSS fractionation between tank bottom and side drains ratio	6.2 ± 0.7	7.3 ± 0.8
Drum filter removal efficiency, %	28.6 ± 3.7*	31.9 ± 3.4*
Settling device removal efficiency, %	37.1 ± 3.3**	77.9 ± 1.6**
Mean water flows		
Makeup water flow, L/min	337 ± 15	278 ± 31
Makeup water flow, % of total recirculating flow	7.0 ± 0.3	6.2 ± 0.7
Flow to drum filter, L/min	4497 ± 32	4333 ± 58
Total flow to culture tank, L/min	4726 ± 36	4514 ± 14
Bottom drain flow, L/min	340 ± 28	340 ± 28
TSS mass balance		
Mean daily feed rate, kg/d	63.5 ± 5.1	100.4 ± 8.6
Mass of TSS entering culture tank, kg/d	16.2	17.6
Mass of TSS exiting culture tank bottom drain, kg/d	8.1	13.6
Mass of TSS exiting culture tank sidewall drain, kg/d	20.8	28.1
Mass of TSS entering RAS w/makeup water, kg/d	0.2	0.2
Mass TSS removed from RAS at bottom of settling device, kg/d	3.4	10.4
Mass TSS discharged from RAS in system overflow, kg/d	4.6	2.6
Mass TSS removed from RAS in drum filter backwash, kg/d	6.5	8.7
Total mass TSS removed from RAS, kg/d	14.4	21.7
Total mass TSS removed from RAS per unit feed fed, %	22.7	21.6
TSS removed by settling device, % of total mass removed	23.4	48.0
TSS removed in system overflow, % of total mass removed	31.7	11.8
TSS removed by drum filter, % of total mass removed	44.9	40.2

Values in the same row with * were tested for statistical significance (ANOVA), values with ** were statistically significant ($P < 0.01$).

would not have provided an estimate of the variability of the removal efficiency data, nor provide the same removal efficiency as reported in Table 1. We found that the mean TSS removal efficiency calculated using these two different approaches could vary by approximately ±S.E.

To control for differences in TSS concentration entering the settling units between the two treatments, TSS concentration entering the settling unit was used as a covariate (regressor) in an analysis of covariance (ANCOVA) using data of concurrent measures of TSS removal efficiency and TSS concentrations entering the settling unit.

3. Results and discussion

3.1. TSS fractionation at the culture tank

The commercial-scale recirculating system maintained relatively low TSS concentrations within the water column of the 150 m^3 Cornell-type dual-drain tank during all trials, e.g., the mean TSS concentration was 3.2 ± 0.3 mg/L and 4.5 ± 0.6 mg/L exiting the culture tank sidewall drain for the swirl separator and radial-flow settler trials, respectively (Table 1). After treatment within the recirculating system and addition of the makeup water, the recirculating water returning to the culture tank only contained an average of 2.4 ± 0.5 mg/L and 2.7 ± 0.3 mg/L of TSS for the swirl separator and radial-flow settler trials, respectively (Table 1).

We suspect that the relatively low TSS concentrations within the culture tank were primarily a result of the effective flushing and fractionation of settleable solids through the tank's bottom–center drain, as discussed elsewhere (Davidson and Summerfelt, 2004). The mean TSS concentration discharged through the culture tank's bottom–center drain averaged 16.5 ± 1.3 mg/L and 27.7 ± 2.6 mg/L, respectively, for the swirl separator and radial-flow settler trials, respectively (Table 1). Differences in TSS concentrations exiting the culture tank were likely due to the higher feeding rate encountered during the radial-flow settler trials, which averaged 100.4 ± 8.6 kg/day compared to 63.5 ± 5.1 kg/day for the swirl separator trials (Table 1). On average, the concentrations of TSS exiting the tank's bottom–center drain were 6.2 ± 0.7 and 7.3 ± 0.8 times greater than the TSS concentration discharged through tank's side-wall drain for the swirl separator and radial-flow settler trials, respectively (Table 1). Davidson and Summerfelt (2004) found that tank hydraulics flushed the majority of waste feed particles from the bottom–center drain of the 9.1 m (30 ft) diameter culture tank within only 3–6 min of their deposition into the tank. In addition, while the culture tank's bottom drain flow only amounted to 7–8% of the tank's total water flow, this relatively small flow still contained approximately 60% of TSS produced within the culture tank in a single pass, assuming that the mass of TSS entering the culture tank consisted of fine solids that proportioned themselves to both tank drains according to the flow split (Table 1). It is also important to note that the mass of TSS entering the culture tank could be either just more or just less than the mass of TSS produced within the culture tank, depending upon its feeding rate (Table 1). This indicates that further improvements in TSS control technology could be made to reduce the TSS concentration in suspension within the recirculating water returning to the culture tank.

3.2. TSS removal across the settling units

The radial-flow settler was more effective at removing TSS than the swirl separator. TSS removal efficiency across the swirl separator and radial-flow settler averaged (±S.E.) 37.1 ± 3.3% and 77.9 ± 1.6%, respectively (Table 1). The ANCOVA shows that treatment differences in TSS removal efficiency were highly significant ($P < 0.001$) as were differences in TSS concentrations entering the two treatment devices. The covariate (TSS concentration of the inflow) used in the ANCOVA was effective in controlling for differences in TSS concentration entering the settling device ($P = 0.0019$). The TSS removal efficiency of the radial-flow settler was less variable than the swirl separator and more consistent over a broad range of TSS concentration of the inflow to the settler (Fig. 4). The TSS removal efficiency of the swirl separator, however, was strongly correlated to the inflow concentration of TSS concentration entering the separator, accounting for 50% of the variability (coefficient of determination, r^2) in solids removal efficiency of the swirl separator. The significant interaction term in the ANCOVA demonstrates that the covariate was important for only the solids removal efficiency of the swirl separator but not for the radial-flow separator (Fig. 4).

The surface-loading rate applied to both settling tank designs was 0.0031 m^3/s of flow per square meter of settling area. In comparison, the Idaho Division of Environmental Quality (1998) has published waste management guidelines that recommend surface-loading rates of 0.00046, 0.0040, and 0.0095 m^3/s flow per square meter surface area for settling basins designed to treat, respectively, a backwash cleaning flow using an off-line settling basin, the full flow to be discharged from a fish farm, and the full flow leaving a

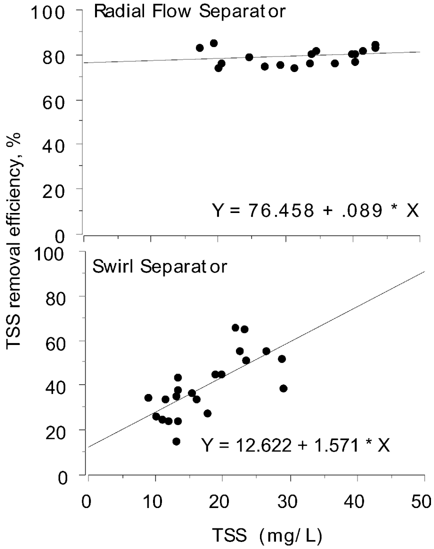

Fig. 4. Relationship between solids (TSS) removal efficiency and concentration of solids inflow for the radial-flow settler and swirl separator. The regression coefficient (0.089) for the radial-flow separator was not statistically significant ($P = 0.39$), but the regression coefficient (1.571) was highly significant ($P < 0.001$) for the swirl separator.

raceway unit through its quiescent zone. The surface-loading rate applied to the settling units evaluated in this paper was just less (i.e., more conservatively designed) than the value that IDEQ (1998) recommends for design of full-flow settling basins and was nearly three times less than the value that IDEQ (1998) recommends for design of quiescent zones. However, the surface-loading rate applied here was nearly 6.8 times greater (i.e., more aggressively designed) than the IDEQ (1998) recommended value for design of off-line settling basins that encounter highly variable flow and concentration fluctuations, which were not the conditions encountered by the settling units evaluated within this study. The relatively conservative surface-loading rate that was applied to both types of settling units in this study was used in an attempt to maximize TSS removal from the relatively small but concentrated bottom-drain discharge exiting the Cornell-type dual-drain tank. A higher surface-loading rate would be expected to cause some decrease in TSS capture efficiency. Veerapen et al. (in press) reports that surface-loading rates on swirl separators as high as 0.0015 m^3/s of flow per square meter of settling area can still produce settleable solids removal efficiencies of approximately 42–53% with model aquaculture solids. Eikebrokk and Ulgenes (1993) do not specify a surface-loading rate but report that swirl separators on average removed 71% of TSS when treating a circular culture tank's bottom–center drain discharge in a single-pass system used for Atlantic salmon broodstock. Note that TSS removal efficiency in a single-pass application are expected to be slightly higher than in a recirculating system application, simply due to the accumulation of fine solids in a recirculating system that settle too slowly to be removed by a settling unit.

Theoretically, settling units in aquaculture should be capable of capturing the majority of the settleable solids entering the unit (Henderson and Bromage, 1988; Wong and Piedrahita, 2003). In this study, the relatively low TSS capture efficiency within the swirl separator was attributed to the formation of hydraulic conditions that were less than ideal in comparison to the more linear flow hydraulics that were created in the radial-flow settler between its inlet structure—located in the tank center—and its 360° perimeter weir (Fig. 3). In addition, the TSS capture efficiency of the swirl separator might be improved with the use of more optimum flow outlet structure design and placement, as have been described by Paul et al. (1991), Andoh (1998), and Veerapen et al. (in press), and with the use of lower surface-loading rates.

Swirl separators have traditionally been used to remove sand and grit particles with high specific gravities from municipal or industrial wastewaters (Paul et al., 1991; Andoh, 1998). The swirl separator tested here appeared to capture all of the slow sinking waste feed pellets, which settled at approximately 14–18 cm/s—about the same as reported by Juell (1991). However, fecal matter from rainbow trout has a specific gravity much closer to that of water than sand and fresh fecal matter has been reported to settle at relatively low velocities (e.g., 0.7–4.3 cm/s), depending upon its size and specific gravity (Warren-Hansen, 1982; Wong and Piedrahita, 2000, 2003). Slower solids settling would occur if the fish do not produce an intact fecal pellet, if the fecal pellets have degraded and broken apart during transport through the culture tank and connecting piping, or if waste solids exist as detached biofilm material (Summerfelt et al., 2001; Wong and Piedrahita, 2003). During these studies, relatively diffuse and 'diarrhea-like' fecal matter was occasionally produced and some of the waste solids treated by the settling unit was detached biofilm, which all have relatively low settling velocities. In addition to the less than optimum hydraulic conditions, particulate matter may have also been re-suspended within the settling unit by the action of fish that occasionally escaped into the settling unit and by the microbial production of gasses within the settled solids at the base of the settling unit's cone. For example, infrequent bubbles were observed to float solids out of both types of settling basin.

In hindsight, a weakness of this study was that no particle size or density data was collected on the solids entering the settling unit during the two trials. An analysis of particle size and density would have determined if equivalent particles were entering the two settling devices. In order make a fair comparison of the two settling devices, equivalent particle size and particle density would have to be assumed. It is possible that uncontrollable conditions (e.g., diarrhea-like fecal matter) producing a smaller mean particle size entering the settling device had only occurred during the trial of the swirl separator. This could explain why the swirl separator TSS capture efficiency was considerably less than measured across the radial-flow separator. Fortunately, another measurement of the relative settleability of the TSS produced during the two trials was recorded, i.e., the TSS fractionation between the culture tank's bottom and side drains. Table 1 indicates that TSS fractionation between the culture tank's bottom and side drains were approximately equivalent in the trial of the swirl separator and the radial-flow settler, averaging 6.2 ± 0.7 and 7.3 ± 0.8, respectively. Therefore, the settleability of the TSS did not appear to be grossly different between the trials of the settling units, which indicates that the test conditions were fair.

3.3. TSS removal across the microscreen drum filters

The TSS concentration entering the microscreen drum filter averaged 3.2 ± 0.3 mg/L and 4.5 ± 0.6 mg/L during the swirl separator and the radial-flow settler trials, respectively. These relatively low inlet TSS concentrations produced the relatively low TSS capture efficiencies that were measured across the microscreen drum filters, i.e., 28.6 ± 3.7% and 31.9% ± 3.4% for the swirl separator and radial-flow settling unit trials, respectively.

3.4. TSS discharges from the recirculating system

The fully recycle system had three locations where solids removal occurred: a one to two times per day manual flush from the bottom of the settling cone, the continuous recirculating system overflow (which was discharged at the settling device overtopping flow), and the frequent drum filter backwash (Fig. 1). Mass balance calculations were made to determine the total mass of TSS removed at each discharge location and the total mass of TSS removed from the recirculating system with respect to the amount of feed fed (Table 1). Percentages were also calculated to determine the portion of solids that were removed at each location. The mass balance indicates that for both trials approximately 21.6–22.7% of the feed fed was removed from the recycle system as waste TSS. The mass balance also indicates that the swirl separator only removed approximately 23% of the total mass of TSS removed from the recirculating system (Table 1). However, when the radial-flow settler was operated in the same recirculating system, it accounted for approximately 48% of the mass of TSS removed from the system daily (Table 1). These results indicate that a large fraction of solids remained suspended within the swirl separator and were discharged in its overflow, instead of being retained in its cone bottom. The mass balance calculations also indicate that the microscreen drum filter accounted for approximately 40–45% of the mass of TSS removed daily from the recirculating system when using either solids settling device (Table 1). In either case, these results indicate that drum filter treatment of the entire recirculating flow does play an important role in preventing elevated TSS concentrations from accumulating within a recirculating system. The remaining TSS were flushed out in the recirculating system overflow, which amounted to approximately 32% of the total mass of TSS removed from the system daily when the swirl separator was used and approximately 12% of the total mass of TSS removed from the system daily when the radial-flow settler was used (Table 1). Note, that the mass of TSS flushed through the recirculating system overflow was relatively high when the concentration of TSS exiting the settling unit was relatively high, e.g., 9.6 ± 0.5 mg/L when the swirl separator was used. With either solids settling device, the percentage of solids discharged through the system overflow would have been significantly reduced (up to three times lower) if the system overflow had discharged at the pump sump where TSS concentrations only averaged 2.2–3.1 mg/L.

4. Conclusions

Relatively low concentrations of TSS can be maintained in recirculating salmonid culture systems that use settling units for treating the dual-drain culture tank underflow and a microscreen drum filter for treating the settling cone supernatant after recombining this flow with the relatively large overtopping flow exiting the culture tank. A radial-flow settler was found to provide approximately twice the TSS removal efficiency of a swirl separator of identical size and surface-loading rate. And, use of a radial-flow settler instead of a swirl separator provided considerably reduced solids loading on the microscreen drum filter, which would be expected to reduce its backwash requirements. Operating the recirculating system with either settling unit still required use of a microscreen drum filter, as the drum filter was found to remove 40–45% of the total mass of TSS removed daily from the recirculating system. In addition, to minimize the mass and concentration of TSS discharged from a coldwater recirculating system within its overtopping flow, this overtopping flow should be discharged from the pump sump where the water has a relatively low TSS concentration.

Additional research is recommended to model and/or evaluate the velocity fields within radial-flow settling units and determine the influence of surface-loading rate and particle settling velocity on TSS capture within radial-flow settlers used in aquaculture applications.

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