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Treatment of rainbow trout (*Oncorhynchus mykiss*) raceway effluent using baffled sedimentation and artificial substrates

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Abstract

The treatment performance of a 6 m wide by 67 m long by 0.8 m deep, baffled sedimentation basin receiving rainbow trout (*Oncorhynchus mykiss*) raceway effluent was evaluated with and without the installation of artificial substrates (Aquamats®). Treatment efficiency was also determined using normal rearing condition effluent loading versus cleaning and harvesting events. Total suspended solids (TSS) removal for the total basin averaged 79% and 71% during normal rearing conditions, as compared to 92% and 79% during cleaning and harvesting operations, when the Aquamats® were installed versus removed, respectively. Total phosphorus (TP) removal by the total basin, with and without Aquamats®, was 20% and 23% during normal rearing conditions as compared to 55% and 65% under cleaning and harvesting conditions, respectively. Higher TP removal during cleaning operations was attributed to sedimentation of particulate fractions. Dissolved nutrient removal (*ortho*-phosphate (OP), total ammonia nitrogen (TAN), nitrate, nitrite, and total organic carbon (TOC)) was not consistent throughout the basin and did not improve when the Aquamats® were installed. A short contact time and periphyton grazing by isopods may have limited the capacity of the Aquamats®.

Calculated retention times with and without Aquamats® for the first half and total basin were 37% and 32% and 27% and 17% less than theoretical values, respectively based on a rhodamine WT dye study. Average surface overflow rates were adjusted accordingly and measured 19.1 m^3/m^2 day when the Aquamats® were installed, versus 14.8 m^3/m^2 day when the Aquamats® were removed for the overall basin. These rates are lower than previous recommendations for treating aquaculture effluents, but resulted in high solids removal and consistently low TSS effluent (average <2 mg/L), which may be necessary for strict discharge permits. Use of the overall basin minimized the occurrence of TSS measurements >2 mg/L by 50%. For the first half of the sedimentation basin, the overflow rate averaged 44.1 m^3/m^2 day with Aquamats® versus 35.8 m^3/m^2 day without Aquamats®. The majority of effluent treatment occurred within the first half of the basin, which was responsible for 84% and 94% of overall TSS removal, 42% and 100% of overall NH_3-N removal and 61% and 80% of overall TP removal during normal and cleaning/harvesting conditions, respectively.

Keywords: Solids removal; Sedimentation; Raceway; Effluent treatment; Tracer; Aquamats®

1. Introduction

Impaired water quality in streams supplying Virginia trout farms have been the focus of various studies (Selong and Helfrich, 1998; Boardman et al., 1998). A TMDL prepared for the Virginia Department of Environmental Quality evaluated impacts to water quality at six trout farms throughout Virginia due to organic solids loading (VWRC, 2002) and identified impacts ranging from moderately impaired to unimpaired (VWRC, 2002).

Solids removal in trout farm effluents has been recommended to reduce pollutant loadings (VWRC, 2002). Facing regulatory pressure, raceway trout farm

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operators are adopting best management practices to improve effluent water quality (Summerfelt, 1999). Such practices include enhanced cleanout of production raceways and effluent treatment such as sedimentation basins for solids and nutrient removal.

Three primary pollutants are discharged from flow-through aquaculture facilities: pathogenic bacteria or parasites, therapeutic chemicals and antibiotics, and metabolic products and food wastes (Beveridge et al., 1991). Metabolic products (dissolved nutrients) and food wastes (solids and particulate nutrients) have been the subject of multiple effluent treatment techniques (Boardman et al., 1998; Hinshaw and Fornshell, 2002; MacMillan et al., 2003; Schulz et al., 2003; Wong and Piedrahita, 2003).

Variations in trout farm effluent water quality can be related to environmental factors such as influent water quality (Clarke, 2003), flow rate (Axler et al., 1997), culture species, fish size (Maillard et al., 2005) and stocking density. Other factors affecting water quality include: feeding techniques (Kelley et al., 1997; Gatlin and Hardy, 2002; Flimlin et al., 2003), frequency of cleaning (IDEQ, 1998), and primary treatment (sedimentation) (Bergheim, 1991; Boardman et al., 1998; IDEQ, 1998).

Reported concentration ranges for trout effluent constituents are shown in Table 1. One significant factor affecting raceway effluent quality is the management condition occurring during the time of water sample collection. Effluent pollutant levels can be many times higher during raceway harvesting or cleaning, due to the resuspension of settled solids (Bergheim et al., 1984; Kendra, 1991; Kelley et al., 1997; Boardman et al., 1998).

The Virginia TMDL study revealed that the majority of nitrogen, phosphorus and organic carbon released from studied trout farms are sediment bound (VWRC, 2002). Others suggest a large variation in particulate nutrient fractions, ranging from 30% to 80% of phosphorus and 7–32% of nitrogen (Cripps, 1995; Summerfelt, 1999; Cripps and Bergheim, 2000). Many authors have concluded that removing suspended solids is the best approach to reduce pollutant loading to receiving streams (Cripps, 1992; Schwartz and Boyd, 1994; Boyd et al., 1998; VWRC, 2002), and sedimentation is the most widely applicable and feasible way for reducing solids and associated nutrients from flow-through trout farms (Hinshaw and Fornshell, 2002; Stechey, 1991; Summerfelt, 1998; MacMillan et al., 2003).

1.1. Settling basins

Three types of sedimentation basins are utilized in raceway production systems: (1) quiescent zones, (2) off-line settling basins, and (3) full-flow settling basins (Hinshaw and Fornshell, 2002; IDEQ, 1998). A quiescent zone is a partitioned section within the production raceway, below the rearing area, which allows for initial separation of settleable solids and trout feces. Quiescent zones must promote settling such that the overflow rate (V_o) is less than the settling velocity (V_s). The reported acceptable range for overflow rates is 817–4320 m^3/m^2 day (2678–14,170 ft^3/ft^2 day) (IDEQ, 1998). Routine cleanout of quiescent zones should be performed as often as possible, and at least once every 1–2 weeks (Westerman et al., 1993; IDEQ, 1998; MacMillan et al., 2003).

Off-line settling basins receive accumulated solids from quiescent zones and/or solids removed through raceway vacuuming. These basins typically receive 0.75–1.55% of the full flow of water through an aquaculture facility (IDEQ, 1998). Therefore, they have

Table 1
Typical water quality characteristics (mg/L) in flow-through trout farm effluents

Study	Water quality parameter concentration (mg/L)								
	pH	DO	TSS	TOC	TAN	NO_3-N	NO_2-N	OP[a]	TP
Axler et al. (1997)			1–8	0.1–4.0				0.01–0.04	0.05–0.06
Bergheim and Brinker (2003)			2–10						0.05–0.3
Boardman et al. (1998)	7.3–7.8	5.7–9.6	1–62		0.02–0.6			0.05–0.32	
Boaventura et al. (1997)	5.9–6.6	7.9–11.4	1–23		0.32–1.52	0.7–2.5	<0.02		0.04–0.70[b]
Dumas et al. (1998)	6.5–7.5				0.6–1.3	0.6–0.8		0.05–0.17	
Fries and Bowles (2002)	7.1–8.8	6.0–11.8	2–97		0.02–0.92				<0.01–0.12
Kendra (1991)	6.8–9.4	5.4–14.3	<1–9		0.02–0.89	0.1–2.4[c]			0.02–0.36
Selong and Helfrich (1998)	7.7–8.2	>7.0				0.3–1.7			0.16–1.09
Schulz et al. (2003)	7.6–7.9	5.8–6.8	9–14			0.66–0.70			0.35–0.37
Viadero et al. (2005)		7.3–10.4	4–12		0.10–0.36				

[a] Orthophosphate (OP).
[b] Value for total phosphates.
[c] Value for nitrate + nitrite.

considerably longer retention times than quiescent zones or full-flow settling basins. The combination of quiescent zones and off-line settling basins is the most commonly used system for trout effluent treatment in concrete raceway systems throughout the U.S. (IDEQ, 1998; Hinshaw and Fornshell, 2002).

On-line, full-flow settling basins receive the full volume of effluent and require large storage volumes to create settling conditions necessary to remove suspended particles. Full-flow basins often function as the only settling treatment mechanism without quiescent zones or off-line settling devices. Henderson and Bromage (1988), Stechey (1991), Boardman et al. (1998), the Idaho Department of Environmental Quality (1998), Summerfelt (1999), and Hinshaw and Fornshell (2002) have described design criteria for full-flow sedimentation basins for aquacultural effluents. The primary design parameters for sedimentation basin efficiency are the settling velocity of the suspended particles that enter a sedimentation basin, scouring velocity created within the basin, surface overflow rate, and hydraulic retention time (Warren-Hansen, 1982).

Trout fecal casts have settling velocities ranging from 2.0 to 5.0 cm/s (0.066–0.164 ft/s), while smaller particles broken down by biodegradation and turbulence settle at much slower rates, ranging from 0.046 to 0.122 cm/s (0.0015–0.0030 ft/s) (IDEQ, 1998). Wong and Piedrahita (2003) estimated the settling velocity for settleable solids in trout effluent as 1.7 cm/s (0.056 ft/s). Warren-Hansen (1982) observed the average settling velocity of solids in trout effluent ranged from 1.7 to 5.0 cm/s (0.05–0.14 ft/s). Higher fecal settling velocities were correlated with increasing fish size. Recommended overflow rates for optimal fish-farm effluent settling are variable (Table 2).

The scouring velocity defined by Camp (1946) and modified by Swamee and Tyagi (1996) calculates a minimum flow-through velocity necessary to flush a specific particle (size and weight) through a settling zone. Particle size studies by Cripps (1995), Boardman et al. (1998), and McMillan et al. (2003) indicated that the majority of individual particles in trout aquaculture sludge range from 5 to 20 μm in diameter. This size corresponds with a minimum scouring velocity 0.20–0.40 m/s. Hence, the horizontal velocity within the basin must not exceed this rate to prevent scouring.

Table 2
Recommended design overflow rates for full-flow sedimentation basin treating trout effluent

Study	Recommended overflow rate
Boardman et al. (1998)	48.9–77.4 m^3/m^2 day (160–254 ft^3/ft^2 day)
IDEQ (1998)	171–342 m^3/m^2 day (561–1123 ft^3/ft^2 day)
Liao (1970)	Less than 120 m^3/m^2 day (394 ft^3/ft^2 day)
Mudrak (1981)	Less than 40.8 m^3/m^2 day (134 ft^3/ft^2 day)
Stechey (1991)	40.8–79.2 m^3/m^2 day (134–260 ft^3/ft^2 day)
Warren-Hansen (1982)	Less than 57.6 m^3/m^2 day (189 ft^3/ft^2 day)

Basin hydraulic studies are critical for validating sedimentation based on flow and settling rate parameters. Short-circuiting and non-uniform flow conditions within a sedimentation basin can result in large differences between actual and theoretical retention times (volume/flow) (Macdonald and Ernst, 1986; Marecos do Monte and Mara, 1987). Baffles can increase flow path lengths and mean retention times in large basins (Pedahzur et al., 1993). Mangelson and Watters (1972) suggested that increasing the length to width ratio (L:W) yields the greatest influence on overall efficiency of waste stabilization as flow approaches plug flow. Arceivala (1983) and Michelsen (1991) recommended that L/W ratios for aquaculture settling basins be greater than 4:1, and ideally more than 8:1.

Tracer studies are effective for calculating average retention times and documenting important hydraulic responses for determining length to width ratios, extent of short-circuiting, and reductions in effective volume due to areas of stagnation (Macdonald and Ernst, 1986; Teefy and Singer, 1990; Pedahzur et al., 1993). Rhodamine WT dye has been used for such studies because it is: (1) water soluble, (2) highly detectable-strongly fluorescent, (3) fluorescent in a part of the spectrum not common to materials generally found in water, thereby reducing the problem of background fluorescence, (4) harmless in low concentrations, (5) inexpensive, and (6) reasonably stable in a normal water environment (Wilson et al., 1986; Field et al., 1995).

1.2. Biofiltration

The dissolved nutrient fractions in trout farm effluent are difficult to remove without biological treatment or filtration (Dumas and Bergheim, 2000; Schulz et al., 2003). Utilizing aerobic microorganism (e.g. *Nitrosomonas* sp. and *Nitrobacter* sp.) growth for nitrification and absorption of dissolved phosphorus by cyanobacteria, biological media filtration (biofiltration) offers a potential treatment option for reducing dissolved inorganic nutrient concentrations in aquacultural effluents (Dumas et al., 1998; Bender et al., 2004). Various studies have been conducted to study biofiltration applications for treating aquacultural effluents, such as bead filtration (Drennan et al., 1995), sand filters (Kristiansen and Cripps, 1996) and wetlands (Adler et al., 1996; Schulz et al., 2003). Given the high effluent volume in flow-through trout farms, operational costs of traditional biofilters used in recirculating systems (submerged filters, trickling filters, pressurized bead filters) make implementation of such technology unfeasible (Summerfelt, 1999). The limitations of sedimentation as the sole process for nutrient removal warrants the need for continued research into low cost alternatives that address dissolved nutrients in addition to nutrients bound to sediments.

Aquamat® biofiltration media is a type of synthetic carpet-like substrate that is suspended vertically in the water column and contains a high effective surface area (200 m^2 per m^2 of material) that is suspended in the water column (Ennis and Bilawa, 2000). This media has been principally used to provide structure for enhancing stocking densities in fish culture ponds (Scott and McNeil, 2001), increase fin growth in raceways (Arndt et al., 2002) and enhance biological processes in ornamental ponds (Ennis and Bilawa, 2000). However, Erler et al. (2004) quantified significant TSS and nutrient removal using Aquamats® in combination with omnivorous fish to treat shrimp farm effluent, while Bratvold and Browdy (2000) observed decreases in ammonia levels using Aquamats® and sand sediment to treat shrimp farm wastewater. These findings support further research of Aquamats® potential benefit for improving trout farm effluent.

The following study addresses the issue of trout effluent treatment through the implementation of a baffled sedimentation basin containing Aquamat® biofiltration media. The specific objectives of work were

1. To evaluate the treatment efficiency of a baffled sedimentation basin by comparing TSS, nutrients and other variables in the influent and effluent;
2. To evaluate treatment variables during normal versus cleaning and harvesting conditions;
3. To determine water treatment achieved through the installation of Aquamat® biofiltration media;
4. To document in-basin hydraulic characteristics for determining actual length to width ratios and surface overflow rates.

2. Methods and materials

2.1. Study site

Four production raceways in series containing rainbow and golden trout (*Oncorhynchus mykiss)* are used for the rearing of approximately 27,000 kg (60,000 lb) of fish per year at the study site. Yearling trout, 12–15 cm (6 in.) are held and fed until they are ready for sale and distribution at an average per fish weight of 0.3–0.7 kg (0.7–1.5 lb).

A freshwater spring (6681 m^3/day, 10 years average) provided source water for the facility. Each concrete-lined production raceway measured approximately 4.5 m wide, 30.5 m long, and 1 m deep (15 ft by 100 ft by 3.3 ft). The outfall from the final production raceway (#4) is directed into an adjacent series of larger, earthen bottom, unused raceways that were used for the construction of a baffled sedimentation basin. The effluent flowed through the basin before and released to a side stream channel that eventually reaches the natural stream reach.

2.2. Sedimentation basin design

The sedimentation basin consisted of two consecutive sections (first and second) each 6.1 m wide by 30.5 m long (20 ft × 100 ft). The total combined surface area for this basin was approximately 372 m^2 (4000 ft^2). Trout effluent entered the basin from a 1 m × 0.5 m high rectangular opening in the concrete wall partition between the sedimentation basin and production raceway #4 (Fig. 1). To promote plug flow conditions, create a serpentine flow path, and increase the retention time, plywood baffling was installed at 7.6 m intervals in the basin. Each baffle consisted of 4.6 m by 0.91 m (15 ft × 3 ft) of reinforced plywood providing a 1.5 m (5 ft) opening for flow-through. The outlet of the basin was regulated by dam boards set at a height to maximize depth throughout the basin (0.61–0.73 m), and created an overflow weir to maintain maximum settling efficiency. A surface scum baffle was installed near the outlet to retain floating particles.

Six mil polyethylene plastic sheeting was placed on the gravel basin bottom to monitor solids accumulation and allow for vacuuming. Depth measurements were made using a 1.5 m (5 ft) grid pattern to determine an average depth for the first and second sections of the basin. Average basin depths and associated basin volumes are provided in Table 3.

Table 3
Average basin depth and volume for the first and second basin sections

Section	Average water depth (m)	Volume (m^3)
First	0.73	136
Second	0.61	113
Overall	0.67	249

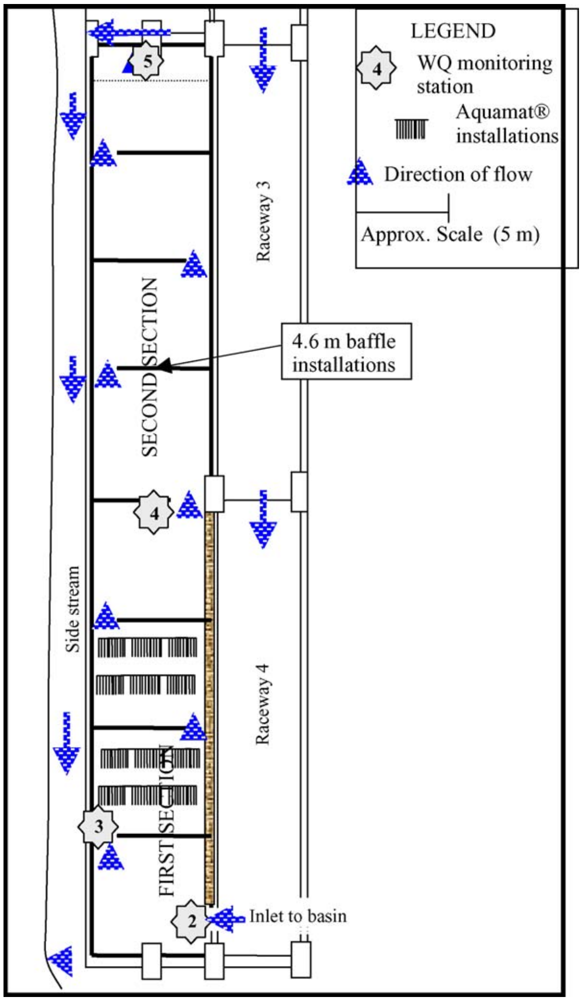

Fig. 1. Plan view of raceways and sedimentation basin.

2.3. Aquamat® biofiltration media

Within the first section of the sedimentation basin, four linear segments of Aquamat® biofiltration media were installed perpendicular to the flow path (Fig. 1). Each segment contained three Aquamat® units (Model:14020-for Fish Hatcheries, Meridian Aquatic Technology, LLC., Calverton, MD). Each unit measured 2 m (6.42 ft) long and 0.91 m (3 ft) high and contained a foam float sleeve to allow Aquamat® strands to hang vertically in the water column. Each unit provided 370 m^2 (4000 ft^2) of effective surface area. In total, 12 Aquamat® units were installed within the first section of the basin providing roughly 4400 m^2 (48,000 ft^2) of available substrate for biofilm growth. An additional 160 m^2 (1700 ft^2) of available surface area for biofilm growth was provided by the basin walls and baffles throughout the first and second sections.

2.4. Water quality monitoring

Water quality parameters (Table 4) were monitored at five sampling locations (Table 5 and Fig. 1). Duplicate samples were collected during normal operation conditions (feeding) at all monitoring stations to evaluate influent versus effluent and to calculate nutrient and solids removal percentages. Monthly sampling is required for the facility's current NPDES permit and therefore was adopted instead of composite sampling. Intensive sampling (4–5 samples per station) was conducted during raceway cleaning and fish harvesting activities throughout the summer and fall 2004 and winter 2005 to examine treatment capacity

Table 4
Water quality parameters and associated methodology used for analysis

Parameter	Methodology
Temperature	YSI, Inc., dissolved oxygen/temperature meter
pH	w/electrosylicate pH probe
Total suspended solids, TSS	Standard Methods 2540 D[a,b]
Total organic carbon, TOC (as C)	Persulfate-ultraviolet oxidation method 5310 C[a,b], Dohmann DC-80 TOC analyzer by Rosemount Analytical, Inc.
Total ammonia nitrogen, TAN (as N)	Salycilicate method, Hach® Method 8155[c,d,e]
Nitrite, NO_2 (NO_2-N)	Dianozation method, Hach® Method 8155[b,c,d]
Nitrate, NO_3 (NO_3-N)	Cadmium reduction method, Hach® Method 8155[c,d]
Orthophosphate, OP (PO_4-P)	Ascorbic acid method, Hach® Method 8048[a,b,c]
Total phosphorus, TP (PO_4-P)	Acid persulfate digestion, ascorbic acid detection method, Hach® Method 8190[a,b,c]
Dissolved oxygen, DO (as O)	YSI, Inc., dissolved oxygen/temperature meter

[a] Method developed/adapted from *Standard Methods* (APHA, 1998).
[b] USEPA approved for wastewater analysis.
[c] Hach company, Loveland, CO, USA.
[d] Method developed/adapted from Federal Register (1979).
[e] Method developed/adapted from Reardon et al. (1966).

Table 5
Water quality monitoring station descriptions

Name	Description
Station 1	Spring inlet to production raceway, at pool where spring surfaces from groundwater, prior to inlet into production raceway #1
Station 2	Outfall/effluent of production raceway #4, at inlet to first section of sedimentation basin
Station 3	First section of sedimentation basin, 7.6 m (25 ft) linearly downstream from inlet, prior to contact with Aquamat® installations, used for comparison to water quality at station 4
Station 4	Sedimentation basin at 30.4 m (100 ft) linearly downstream from inlet, at outlet of the first section, inlet to second section, downstream from Aquamat® installations
Station 5	Outfall of the second section of the sedimentation basin prior to side stream

during higher solids and nutrient loading. Sampling throughout the basin was designed to compare treatment efficiency during: (1) normal operations versus cleaning and harvesting, (2) with and without Aquamats®, and (3) the first half (first section) versus overall basin (first and second sections combined).

2.5. Flow monitoring

Flow measurements were made at the rectangular outfall of production raceway #2. Using the Francis formula for sharp-crested weirs (Wood, 1974), water depth measurements were converted to flow (m^3/day) across the 2.44 m wide weir.

2.6. Tracer study

Rhodamine WT dye tracer monitoring was used to evaluate flow characteristics throughout the sedimentation basin with and without Aquamats®. A known mass of dye was released as a slug at the basin inlet. Following release, water samples were collected at monitoring stations 4 and 5 at 2–20 min intervals to document hydraulic conditions of the first and second sections of the basin. A fluorometer (Turner Designs Model 450) was used to analyze sample dye concentrations. Field calibration was performed using serial dilutions of known tracer concentrations to establish a calibration curve for the fluorometer. Constant sample temperature was maintained during analysis to ensure accurate concentration determination (Wilson et al., 1986).

3. Results

3.1. Normal operations basin performance

Solids removal increased with increasing basin volume under normal operations loading (Table 6). Average TSS removal at the basin outlet was slightly higher (8% difference) when the Aquamats® were installed (79%), as compared to when they were removed (71%). However, results from samples collected at station 4 (first section) indicate a greater difference (17%) in solids removal with Aquamats® installed (72%), versus when they were removed (55%).

Removal of TP and TAN increased with increasing basin volume as 18% TP and 12% TAN removal

Table 6
Average removal efficiency under normal operation loading

Operation	Station	TSS	TOC	TAN	NO_2-N	NO_3-N	OP	TP-P
Aquamats® installed								
Ave. influent WQ (mg/L)	2	4.8	1.24	0.37	0.031	1.6	0.15	0.17
	3	51% ($n = 7$)	−5% ($n = 7$)	5% ($n = 7$)	7% ($n = 7$)	7% ($n = 7$)	13% ($n = 7$)	4% ($n = 7$)
	4	72% ($n = 7$)	−4% ($n = 7$)	5% ($n = 7$)	−2% ($n = 7$)	12% ($n = 7$)	11% ($n = 7$)	9% ($n = 7$)
	5	79% ($n = 7$)	−8% ($n = 7$)	14% ($n = 7$)	3% ($n = 7$)	−3% ($n = 7$)	21% ($n = 7$)	20% ($n = 7$)
Aquamats® removed								
Ave. influent WQ (mg/L)	2	2.7	0.99	0.33	0.01	1.28	0.09	0.10
	3	44% ($n = 4$)	−4% ($n = 2$)	1% ($n = 4$)	0% ($n = 4$)	−6% ($n = 4$)	5% ($n = 4$)	8% ($n = 4$)
	4	55% ($n = 4$)	−37% ($n = 2$)	12% ($n = 4$)	8% ($n = 4$)	6% ($n = 4$)	16% ($n = 4$)	18% ($n = 4$)
	5	71% ($n = 4$)	−11% ($n = 2$)	27% ($n = 4$)	−4% ($n = 4$)	12% ($n = 4$)	22% ($n = 4$)	23% ($n = 4$)

n-Values represent the number of individual sampling events during normal operations. The calculated removals percentages for each event were determined comparing inlet concentrations. These percent values were combined to obtain an overall average percentage removal.

Table 7
Average removal efficiency under cleaning and harvesting loading

Operation	Station	TSS	TOC	NH_3-N	NO_2-N	NO_3-N	OP	TP-P
Aquamats® installed								
Ave. influent WQ	2	22.3	1.43	0.34	0.03	1.47	0.25	0.33
	3	56% ($n = 3$)	6% ($n = 3$)	15% ($n = 3$)	8% ($n = 3$)	−20% ($n = 3$)	21% ($n = 3$)	34% ($n = 3$)
	4	89% ($n = 3$)	12% ($n = 3$)	9% ($n = 3$)	8% ($n = 3$)	−1% ($n = 3$)	37% ($n = 3$)	53% ($n = 3$)
	5	92% ($n = 3$)	20% ($n = 3$)	0% ($n = 3$)	−3% ($n = 3$)	14% ($n = 3$)	42% ($n = 3$)	55% ($n = 3$)
Aquamats® removed								
Ave. influent WQ	2	12.2	1.08	0.26	0.01	1.51	0.28	0.48
	4	73% ($n = 3$)	−3% ($n = 2$)	17% ($n = 3$)	12% ($n = 3$)	5% ($n = 3$)	26% ($n = 3$)	39% ($n = 2$)
	5	79% ($n = 3$)	−4% ($n = 2$)	16% ($n = 3$)	17% ($n = 3$)	−11% ($n = 3$)	46% ($n = 3$)	61% ($n = 2$)

n-Values represent individual cleaning and harvesting events. An average value from each event was combined to obtain an overall average for comparison to inlet concentrations and determining average percent removal.

occurred within the first section while 23% of TP and 27% of TAN was removed by the total basin when the Aquamats® were removed. With the Aquamats® installed, 9% TP and 5% TAN removal occurred in the first section, while 20% of TP and 14% of TAN was removed by the total basin. Removal of OP closely followed total phosphorus removal indicating the majority of phosphorus was in the dissolved fraction (Table 6). Other nutrient parameters (nitrate, nitrite, and TOC) were not effectively removed by the sedimentation basin regardless of whether the Aquamats® were present. TOC increased through the sedimentation basin resulting in no removal. Average influent TSS concentrations during normal operation conditions were generally low (2.7–4.8 mg/L).

3.2. Cleaning and harvesting basin performance

Cleaning and harvesting activities resulted in higher influent pollutant loading than observed under normal operation conditions (Table 7). For the total basin, TSS and TP removal averaged 92% and 55%, respectively when the Aquamats® were installed. Without Aquamats®, average TSS and TP removals declined to 79% and 61%, respectively for the overall basin. In the first section, 89% TSS and 53% TP removal occurred when the Aquamats® were installed, versus 73% TSS and 39% TP removal without Aquamats®.

Removal of TAN and nitrite did not occur in the sedimentation basin when the Aquamats® were installed and nitrate removal was minimal occurring only in the second half of the basin 14% (Table 7). OP removal ranged from 37% at station 4 to 42% at station 5, while TOC removal increased from 12% at station 4 to 20% at station 5. Dissolved nutrient removals when the Aquamats® were removed were inconsistent with observations when they were installed. Without Aquamats®, 17% (station 4) and 16% (station 5) TAN and 12% (station 4) and 17% (station 5) nitrite removals occurred. Concentrations of TOC and nitrate were found to increase through the sedimentation basin resulting in no removal (Table 7). *Ortho*-phosphate removal increased from 26% at station 4 to 46% at station 5.

3.3. Basin hydraulics and tracer study

Results from the tracer study (Figs. 2 and 3) found that calculated retention times both with and without the Aquamats® installed were considerably shorter than theoretical values (Table 8). The calculated retention time (time to reach 50% dye recovery) for the first section of the sedimentation basin was 34 min with Aquamats®, and 37 min without Aquamats®, as compared to a theoretical retention time of 54 min. These data indicate that 32–37% of the basin volume in the first section was lost as dead space due to flow short-circuiting. For the total basin, calculated retention times were 72 min with Aquamats® and 82 min without

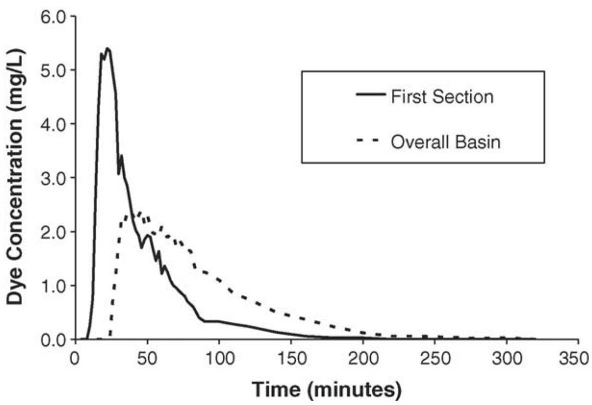

Fig. 2. Tracer dye concentrations vs. time, Aquamats® installed.

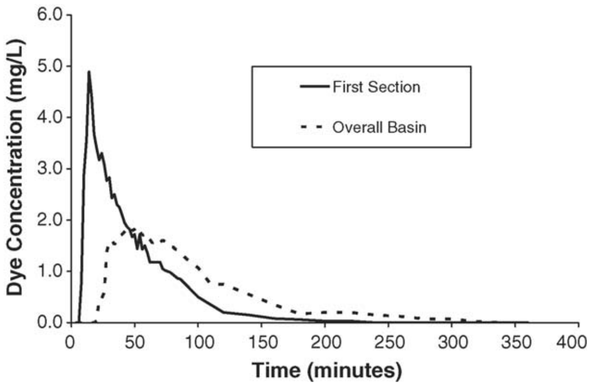

Fig. 3. Tracer dye concentrations vs. time, Aquamats® removed.

Aquamats®. Compared to a theoretical retention time of 99 min, calculated retention times indicate overall dead space volumes of 27% and 17%, with and without Aquamats®, respectively.

Given the observed volume losses, average surface overflow rates (V_o) were determined for monitoring periods with and without Aquamats® (Table 8). For the first section, an average V_o of 44.1 m^3/m^2 day was determined when the Aquamats® were installed versus 35.8 m^3/m^2 day when the Aquamats® were removed. These rates correspond with adjusted average retention times of 24 and 29 min, respectively for the first section. For the total basin, V_o averaged 19.1 and 14.8 m^3/m^2 day with and without Aquamats®, resulting in adjusted retention times of 51 and 66 min, respectively.

Based on a flow of 4550–5762 m^3/day, horizontal flow-through velocities ranged from 0.009 to 0.014 m/s at the widest channel sections (6.1 m) and 0.036–0.057 m/s at the 1.5 m baffle openings. These velocities were well below the minimum scouring velocities (0.2–0.4 m/s) necessary to cause resuspension of 5–20 μm settled particles.

4. Discussion

4.1. Treatment performance

The total sedimentation basin effectively removed TSS (71–92% removal) from raceway effluent during: (1) normal operations and (2) cleaning and harvesting. Installation of the Aquamat® biofiltration media resulted in enhanced solids removal, especially during cleaning and harvesting when TSS concentrations were highest. However, maximum influent TSS loading was observed during periods when the Aquamats® were installed. This may account for the increase removal performance, as suggested by Kelley et al. (1997) who found that solids removal by a sedimentation basin without artificial substrates increased with influent solids concentration. Creating replicate influent pollutant concentrations between treatments (with and without the Aquamats®) was difficult due to the constantly varying stocking density within the facility, harvesting loads, and accumulated solids within the production raceways during cleaning activities. Despite these concerns, the placement of this media perpendicular to flow likely served as a physical barrier to flow, reducing turbulence and aiding in TSS removal as flow passed through the mats. Visual observations of an enhanced sludge buildup below the Aquamat® segments in comparison to the surrounding basin sludge layer indicated the media was providing an additional mechanism for TSS removal. This is consistent with the findings of Erler et al. (2004) who found that Aquamats® enhanced particulate solids settling in batch reactors treating shrimp farm effluent.

Higher TP removal occurred during cleaning and harvesting, and may be attributed to a higher fraction associated with particulates. For example, influent TP during a cleaning event on 25 February 2005 averaged

Table 8
Sedimentation basin hydraulic characteristics

Parameter	Result	
	First section (station 4)	Total basin (station 5)
During tracer study (Q = 3623 m^3/day)		
Theoretical ret. time (V/Q) (min)	54	99
Calc. ret. time—Aquamats® installed (min)	34	72
Calc. ret. time—Aquamats® removed (min)	37	82
% dead space—Aquamats® installed (%)	37	27
% dead space—Aquamats® removed (%)	32	17
During WQ monitoring		
Adj. overflow rates: Aquamats® installed (m^3/m^2 day)	44.1	19.1
Adj. overflow rates: Aquamats® removed (m^3/m^2 day)	35.8	14.8

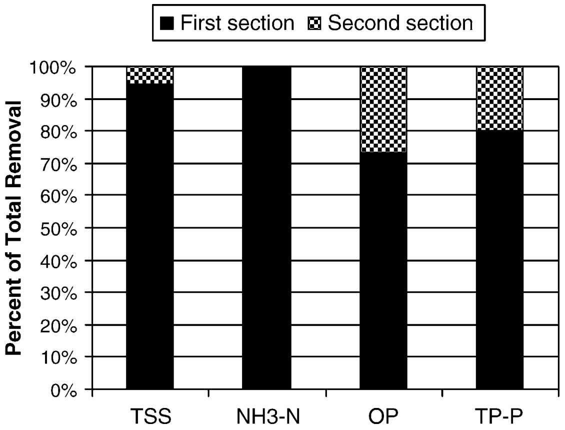

Fig. 4. Removal contributions by section during cleaning and harvesting activities.

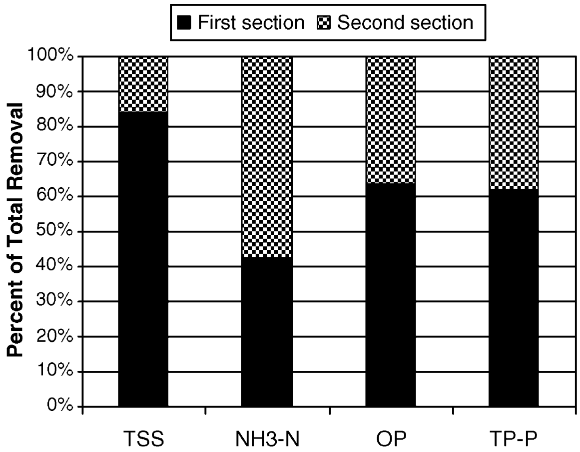

Fig. 5. Removal contributions by section during normal operations.

0.60 mg/L and resulted in a 70% removal at station 5, while on 10 January 2005, influent TP averaged 0.28 mg/L resulting in a 0.35% removal at station 5.

During cleaning and harvesting, the majority of effluent treatment (94% of total TSS, 100% of total TAN, 73% of total OP, and 80% of total TP removals) occurred within the first section of the basin (Fig. 4). This suggests that the second section provided little additional treatment. However, the additional settling in the second section may have been beneficial for maintaining low TSS effluent ($\leq$2 mg/L) even during higher loading conditions. Of the 23 grab samples collected during cleaning and harvesting conditions, seven samples exceeded 2 mg/L at station 5, as compared to 13 samples at station 4. Greater sedimentation must be weighed versus the additional costs associated with cleanout and maintenance of the basin, and space availability. Settled solids accumulated throughout the second section, particularly at the outlet surface particle collector.

During normal operations (feeding), the first section of the basin was still responsible for 84% of overall TSS removal, but provided a more distributed contribution to total removal of nutrients (42% of total TAN, 64% of total OP, and 62% of total TP removal) (Fig. 5). These data represent treatment during the majority of operating conditions, and suggest that the overall basin may not be oversized when trying to maintain strict effluent discharge requirements. The observed increase in TOC concentrations throughout the basin may be attributed to breakdown of solids collecting in the basin, and highlight the disadvantage of storing solids in full-flow sedimentation basins, as suggested by Cripps and Bergheim (2000).

Of the 46 total samples collected at stations 4 and 5, only 2 samples collected at station 4, had greater than 6 mg/L TSS. Henderson and Bromage (1988) found full-flow settling ponds were ineffective at reducing effluent TSS below 6 mg/L. However, the longer retention time of the total sedimentation basin (51–66 min during water quality monitoring) and correspondingly low V_o (14.8–19.1 m^3/m^2 day) in this study produced results consistent with Boardman et al.'s (1998).

Influent TSS loads during normal operations were low, averaging 4.5 mg/L, while higher solids loading (17.1 mg/L avg.) occurred during cleaning and harvesting. This is because raceway maintenance resuspends large sludge particles, which though few in numbers, are much heavier and can contribute significantly to TSS, as observed by Kelley et al. (1997).

Higher pollutant loading was related to higher trout stocking densities (Table 9). The highest influent TSS, TAN, PO4-P and TP occurred when trout densities were above 10,500 lb. Lowest influent loads occurred when densities were at their lowest.

4.2. Aquamat® biofiltration

Despite the installation of the Aquamats® to promote biofiltration conditions, dissolved nutrient reductions were minimal. In fact, removal percentages of TAN and OP during normal operations at station 4 were found to be higher (12% and 16%, respectively) when the Aquamats® were removed, than compared to when they were installed (5% and 11%, respectively). The calculated retention times of 24–29 min for the first section proved to be too short for biological metabolism of dissolved nutrients, which would be expected based on research by Erler et al. (2004) who found enhanced nutrient removal using Aquamats® using a retention time of 55 h. Standard wastewater applications using Aquamats® in aerated lagoons report average retention times up to 96

Table 9
Comparison of pollutant loads vs. production stocking density

Month	Ave. stock (kg)	Average production effluent concentrations (mg/L)					
		N	TSS	TAN	NO_3-N	OP	TP
June-2004	10684	2	8.6	0.58	1.6	0.17	[a]
July-2004	10973	3	2.2	0.41	2.0	0.12	0.13
Aug-2004	15612	2	3.1	0.24	1.7	0.14	0.14
Dec-2004	22334	6	6.2	0.43	1.3	0.16	0.20
Jan-2004	23658	1	4.8	0.35	1.9	0.12	0.13
April-2004	1110	1	1.3	0.22	0.8	0.06	0.08
June-2005	7672	1	4.4	0.18	0.5	0.06	0.07

[a] TP not analysed.

days to achieve sufficient solids and nutrient removal (Westerman and Argo, 2002). Summerfelt (1999) recommended that fluidized-sand biofilters or trickling filters were the only types of filters capable for cost-effectively treating high flows (>4000 L/min) such as those occurring in this study. However, the infrastructure costs of such systems are still considerable and may not be feasible for small trout farms.

Another limiting factor was the abundant presence of sow bugs (isopods) that rapidly grazed bacteria and algal growth that developed on the mats and baffle surfaces. Uncontrolled insect grazing is an important variable when considering Aquamat® applications.

4.3. Hydraulic characterization

Dye recovery of 90–94% indicated a good calibration of the fluorometer and minimal losses from adsorption or basin leaks. The calculated retention time was significantly shorter than the theoretical retention time due to dead spaces created by short-circuiting. The difference between the theoretical and calculated retention times provides an important correction factor for adjusting surface overflow rates to more accurately describe hydraulic conditions within the basin.

Less dead space volume for the overall basin (27% Aquamats® installed, 17% removed) compared to the first section (37% Aquamats® installed, 32% removed) corresponds with a more than doubling of the L:W ratio. Visual records of dye movement were used to identify the principal flow path through the baffled basin. Resulting L:W ratios for the first section and the overall basin were found to be 6.8 and 15.4, respectively. These data suggest that minimal short-circuiting occurred in the second section of the basin, since the calculated retention time for the total basin was closer to the theoretical value. Higher L:W ratio and improved retention efficiency of the overall basin are consistent with studies by Mangelson and Watters (1972), Arceivala (1983), and Michelsen (1991). The high velocity influent water to the first section may have accelerated tracer conveyance, increasing short-circuiting and estimated dead space volume for the first section.

Average V_o of 35.8 and 43.4 m^3/m^2 day for the first section and 14.8 and 19.1 m^3/m^2 day for the total basin and were lower than those recommended by Stechey (1991), Boardman et al. (1998), and IDEQ (1998), and less than the maximum overflow rates recommended by Liao (1974), Mudrak (1981), and Warren-Hansen (1982) for optimal TSS removal. High TSS removal observed in this basin configuration suggests that V_o, much lower than previous recommendations, would be required to consistently maintain low TSS effluent.

Although the sedimentation basin maintained flow-through velocities that should prevent resuspension of particles, prolonged storage of solids within the basin may lead to increased particle degradation, decreased particle size (Boardman et al., 1998), and additional release of dissolved nutrients (Garcia-Ruiz and Hall, 1996) and BOD (Mathieu and Timmons, 1993). The large size of this basin design would require a significant labor investment to routinely remove accumulated solids. Traditional vacuuming is time consuming, and can resuspend small solids in the effluent, as evident in the increased TSS loads observed during raceway cleaning. Final design considerations must address these operational concerns while achieving discharge permit criteria.

5. Conclusion

- The baffled sedimentation basin receiving rainbow trout (*O. mykiss*) farm effluent was highly effective at removing TSS during normal (71–79% removal) and cleaning and harvesting (79–92% removal) operations;
- Increased TSS removal was observed when Aquamat® biofiltration media was installed within the first section of the basin;

- The first section of the basin provided the majority of TSS removal during both normal (84% of total TSS removal) and cleaning and harvesting conditions (94% of total TSS removal);
- Doubling the basin volume and surface area provided minimal improvement in overall effluent quality, but did reduce the occurrence of TSS measurements over 2 mg/L by over 50% during cleaning and harvesting;
- Removal of dissolved nutrients (TAN, nitrate, and nitrite), with the exception of OP was inconsistent through the basin and was not enhanced by the installation of Aquamats®;
- Calculated retention times for the first section and overall basin were 32–37% and 17–27% shorter than theoretical values, respectively;
- Hydraulic efficiency increased with increasing *L*:*W* ratios;
- Reported surface overflow rates, adjusted to account for dead space volumes due to short-circuiting, were less than those recommended for treatment of aquacultural effluents;
- The high TSS removal with this basin design indicates that surface overflow rates, much lower than previous recommendations, combined with routine cleanout of settled solids, would be required to consistently maintain low solids effluent (<2 mg/L).

The evaluation of this treatment option for raceway effluents identifies important monitoring and design criteria that are critical for sedimentation basin efficiency. It is hoped that this study will guide decision making for considering treatment alternatives for raceway systems.

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