Treatment of Rainbow Trout (*Oncorhynchus mykiss*) Raceway Effluent Using Baffled Sedimentation and Artificial Substrates

and

Characterization of Nutrient Leaching Rates from Settled Rainbow Trout (*Oncorhynchus mykiss*) Sludge

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Treatment of Rainbow Trout (*Oncorhynchus mykiss*) Raceway Effluent Using Baffled Sedimentation and Artificial Substrates.

Nathan T. Stewart

(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 with 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 total TSS removal, 42% and 100% and 61% and 80% of total TP removal during normal and cleaning/harvesting conditions, respectively.

Characterization of Nutrient Leaching Rates from Settled Rainbow Trout (*Oncorhynchus mykiss*) Sludge.

Nathan T. Stewart

(Abstract)

The leaching of nutrients from settled rainbow trout (*Oncorhynchus mykiss*) sludge into overlying water was evaluated over a 7 day period. Nutrient leaching was assessed in a stagnant reaction tank and one agitated by aeration to simulate turbulent conditions in stocked production raceways. Leaching of total phosphorus (TP), *ortho*-phosphate (OP), total Kjeldahl nitrogen (TKN), total ammonia nitrogen (TAN), and total organic carbon (TOC) occurred rapidly during the first 24 h in both stagnant and agitated conditions. The highest 24 h leaching occurred in the agitated tank, and power regression equations accurately described the varying rates of increasing TP, OP, TAN and TKN. In the stagnant tank, linear increases of TP, OP, TKN and TAN concentrations occurred during the first 24 h. These linear increases continued from day 2-7, but at slower rates than occurred during the first 24 h. Average nutrient leaching rates (mg leached/g sludge-h);(dry weight basis) were calculated based on linear concentration increases. In the agitated tank, nutrient concentrations decreased after 60 h, as aerobic bacterial uptake and/or chemical precipitation was suspected. Therefore, average leaching rates could not be determined.

These findings reveal that daily cleanout of settling areas could eliminate the release of TP, OP, TAN, TKN, and TOC from settled solids by 66%, 65%, 39%, 76% and 51%, respectively, as compared to weekly cleanout schedules. Sustained leaching rates indicate nutrient release will likely continue beyond 7 days. This information suggests aggressive and continuous sludge management is most beneficial for maintaining high water quality and regulatory discharge compliance in fish production.

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Chapter 1: Literature Reviews

1.1 Literature Review: Treatment of Rainbow Trout (Oncorhynchus mykiss) Raceway Effluent Using Baffling and Artificial Substrates.

The total value of all trout sales, both fish and eggs, received by trout growers in the 20 selected States totaled $68.7 million during 2004, an increase of 7% from 2003 (NASS, 2004). Although the state of Idaho accounted for the largest percentage of trout production (61%) in 2004, Virginia contributed for roughly 1.3 percent of the total US fish and egg sales through fifteen different farm proprietors generating over $924,000 (NASS, 2004).

Over the past five years, the number of Virginia trout farmers has dramatically decreased from 40 in 1999 to 16 in 2004 (NASS, 2004). Though fluctuations in the trout market can affect farm openings and closures, increasing regulation on facility effluent discharges poses the most significant threat to the feasibility and viability of trout farm operations in the state. (Selong, 1997).

Selong and Helfrich (1998) assessed effluent impacts from five Virginia trout farms on downstream water quality, periphyton production, and composition of macroinvertebrate and fish communities. Observed impacts included increased substrate embeddedness, periphyton, and pollution tolerant macroinvertebrate populations, combined with decreased dissolved oxygen (DO), macroinvertebrate richness, and density of pollution sensitive taxa (mayflies, stoneflies, and caddis flies). Their study also observed that settling ponds at two farms effectively reduced nutrient loadings downstream. A TMDL conducted by the Virginia Water Resources Center (2000), evaluated impacts to water quality at six trout farms throughout the state. This study identified impact classifications ranging from moderately impaired to unimpaired. Moreover, these findings specified solids removal as the primary regulatory measure for reducing pollutant loadings to receiving streams (VWRC, 2002).

Three primary pollutants discharged from flow-through aquaculture facilities are pathogenic bacteria or parasites, therapeutic chemicals and antibiotics, and metabolic products and food wastes (Beveridge et al. 1991). Metabolic products (dissolved nutrients and dissolved oxygen uptake) and food wastes (solids and particulate nutrients) have received extensive research to characterize trout farm effluents (Kendra, 1991; Axler et al., 1997; Boaventura et al., 1997 s; Kelley et al., 1997; Boardman et al., 1998; Wong and Piedrahita, 2000; Bergheim and Brinker, 2003; Viadero et al., in press). Analysis of trout farm effluents have identified that the majority of nitrogen, phosphorus and organic carbon are sediment bound (VWRC, 2002). Solids in trout farm effluent carry 7-34% of total nitrogen and 30-80% of total phosphorus in raceway effluent (Cripps and Bergheim, 2000). Removing solids from effluent streams can provide an effective means for reducing pollutant loading to receiving streams (Cripps, 1992; Schwartz and Boyd, 1994; Boyd et al., 1998; VWRC, 2002).

Variations in trout farm effluent water quality can be related to environmental factors such as influent water quality and flow rate (Axler et al., 1997), culture species, fish size (Maillard et al., in press) and stocking density. Other factors affecting effluent quality include facility management: feed types (Kelley et al., 1997; Flimlin et al., 2003), frequency of cleaning (IDEQ, 1998), and sedimentation (Bergheim et al., 1991; Boardman et al., 1998; IDEQ, 1998). Effluent pollutant levels can be many times higher than during raceway harvesting or cleaning (Bergheim et. al., 1984; Kendra, 1991; Kelley et al., 1997; Boardman et al., 1998).

To maintain high effluent quality and comply with increasing regulations, trout farmers must implement best management practices such as enhanced cleanout of production raceways and effluent treatment techniques such as sedimentation basins or mechanized systems. Treating effluent from raceway systems is often compromised due to the large volumes of water released. Conventional sedimentation and microscreen filtration processes have been effective at removing large solids (40-100 µm), but not dissolved or fine solids (< 20-30 µm) (Chen et al., 1993; Heinen et al., 1996).

1.1.1 Microscreen filtration

Microscreen filters are sieves that remove suspended particles larger than the filter screen openings. Solids are removed from the screens by backwashing, vibration, or raking, which can occur several hundred or thousand times per day (Libey, 1993). Backwash volumes of concentrated solids have been reported as 0.2-2.0% of the total passing flow. Summerfelt (1999) reports microscreen filters have been effective at removing 68-80% of total suspended solids (TSS) in flow-through systems.

Microscreen filters are attractive for the following reasons: (1) given their multiple backwash cycles they can remove solids from large flows, (2) they remove solids from within the flow preventing additional nutrient release from particle degradation, and (3) they require little space and are easy to install (Summerfelt, 1999). Disadvantages of these systems include increased maintenance and high water pressure needed for backwashing cycles. The mesh sizes for microscreens are limited by operational factors such as hydraulic loading and backwash requirements for fine particle removal (Cripps, 1995). These factors can also limit the applicability of such technology if high flows are required.

1.1.2 Sedimentation

Three types of sedimentation approaches are used in raceway trout production systems: quiescent zones, off-line settling basins, and full-flow settling basins (Hinshaw and Fornshell, 2002). A quiescent zone is an area within a production raceway, downstream from the rearing area that allows for initial separation of settleable solids and trout feces. Typically, a screen excludes fish from the quiescent zone to allow for undisturbed settling. Quiescent zones are most effective when installed in every raceway. The design of quiescent zones must promote settling such that the surface overflow rate (V_o) is less than the settling velocity (V_s). The reported acceptable range for quiescent zone overflow rates is 817-4,320 m^3/m^2-day (2,678 – 14,170 ft^3/ft^2-day) (IDEQ 1998).

Quiescent zones act as an initial pretreatment for solids that collect within production areas, which are then transported by gravity or pumping to off-line settling basins for additional settling biological treatment. Vacuuming of quiescent zones is the most common method for solids removal (IDEQ 1998). Additional quiescent zone solids removal designs are described by the Idaho Department of Environmental Quality (1998), and include broom or squeegee pushing accumulated solids to an installed vacuum port at one end of the quiescent zone. Another design consists of cone-shaped or sloped floors that direct settled solids to a vacuum port at the lowest point. This design allows for continual solids removal. However, problems associated with such alternative designs include resuspension of solids during sweeping and sludge buildup on inadequately sloped floors due to the low viscosity of trout feces (IDEQ 1998).

Routine cleanout of quiescent zones should occur as often as possible. Mathieu and Timmons (1993) recommended trout wastes be removed within 5 days based on BOD consumption rates. Other literature recommends solids removal schedules not exceed two weeks (IDEQ, 1998).

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 considerably long retention times. 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 US (Hinshaw and Fornshell, 2002; IDEQ, 1998).

Because directing flow to off-line basins often requires pumping networks, solids particles requiring sedimentation are smaller (McMillan, et al., 2003). Settling velocities reported by IDEQ (1998) range from 0.045-0.092 cm/sec (0.00151-0.00302 ft/sec). A depth of 0.76 m (2.5 ft) or greater is adequate for off-line basins that are routinely cleaned monthly to avoid excessive solids buildup. Longer periods between cleanout allow greater opportunity for stored solids to break down and release additional dissolved nutrients into receiving waters (IDEQ, 1998). Linking off-line settling basins in series can improve solids collection. As well, increasing depth at basin inlets can allow for additional storage capacity where the majority of solids settle quickly. This can reduce the potential for scouring and resuspension, and can also facilitate solids removal by consolidating solids in a local area (IDEQ, 1998).

Algal blooms can be prevalent in off-line settling basins, and can be controlled by aquatic algaecides and skimmer baffle installations which draw water from below the surface. Skimmer baffles allow floating moss and solids to block out sunlight preventing further algal growth and minimize TSS loads associated with floating material (IDEQ, 1998).

On-line, full-flow settling basins receive the full volume of effluent. Therefore, they require larger storage volumes to create quiescent settling conditions. Full-flow basins often function as the only settling treatment mechanism without quiescent zones or off-line settling devices. The primary design parameters for both full-flow and off-line sedimentation basin efficiency are: the settling velocity of the influent suspended particles, scouring velocity created within the basin, surface overflow rate, and hydraulic retention time (Warren-Hansen, 1982, Fornshell, 2001).

Most raceway effluent contains < 500 mg/L total TSS (Fornshell, 2001). Therefore, discrete particle settling (settling where particles maintain their size and shape) is the primary settling process in the sedimentation of raceway effluent. The settling velocity (V_s) of discrete particles is described in Metcalf and Eddy, Inc. (2003) by Stoke's Law:

$$V_s = \left[\frac{8g(\rho_s - \rho)d^2}{18\mu} \right] \qquad \text{(Eq. 1)}$$

Where, ρ_s = mass density of a particle (kg/m^3 or lb/ft^3)

ρ = mass density of fluid (kg/m^3 or lb/ft^3)

g = acceleration due to gravity (9.81 m/sec^2 or 32.2 ft/sec^2)

d = diameter of a particle (mm or inches)

μ = dynamic viscosity of water

IDEQ (1998) identified large trout fecal casts as having settling velocities ranging from 2.0-5.0 cm/sec (0.066-0.164 ft/sec), while smaller particles, broken down through biodegradation and turbulence, settle at much slower rates ranging from 0.046-0.122 cm/sec (0.0015-0.0030 ft/sec). Wong and Piedrahita (2003) measured average settling velocity for settleable solids in trout effluent as 1.7 cm/sec (0.056 ft/sec). Warren-Hansen (1982) observed the average settling velocity of solids in trout effluent was more variable, ranging from 1.7 to >5.0 cm/sec (0.05 - >0.14 ft/sec). Higher fecal settling velocities were correlated with increasing fish size.

The settling velocity (V_s) is used in comparison with the surface overflow rate. The overflow rate (V_o) (Eq. 2) is equivalent to the hydraulic load:

$$V_o = \frac{Q}{A} \qquad \text{(Eq. 2)}$$

where, Q = flow (m^3/day),

A = surface area (m^2)

Literature recommended overflow rates for optimal fish-farm effluent settling show also indicate a large variation (Laio 1970; Mudrak, 1981, Warren-Hansen, 1982; Stechey, 1991; Boardman et al, 1998; IDEQ, 1998). The highest recommended V_o reported by IDEQ (1998) was 171-342 m^3/m^2-day (561-1123 ft^3/ft^2-day), where as Mudrak (1981) recommended V_o <40.8 m^3/m^2-day (134 ft^3/ft^2-day). Knowing a target particle size to be removed, the associated settling velocity

(V_s) can then be compared to the V_o to determine if the particle will likely settle (V_s>V_o), or remain in suspension (V_s<V_o) and be flushed through the system.

Proper basin design must also prevent scouring. The scouring velocity equation (Eq.3) developed by Camp (1946) calculates a minimum flow-though velocity (V_s) necessary to "scour" a specific particle size and weight through a settling zone.

$$V_{scour} = \left[\frac{8\beta(\rho_s - 1)gd}{f} \right]^{\frac{1}{2}} \qquad \text{(Eq. 3)}$$

Where, β = constant for type of scoured particles (0.06 for sticky grit [Metcalf 1972])

ρ_s = specific gravity of scoured particle (1.476 for trout feces [ ])

g = acceleration due to gravity (32.2 ft/sec^2)

d = diameter

f = Dacry-Weisbach friction factor

Swamee and Tyagi (1996), improved upon Camp's formula to provide a design equation for the Darcy-Weisbach friction factor (f) that relates basin geometry and flow.

$$f = 0.223\left(\frac{\nu B}{Q}\right)^{2.5} \qquad \text{(Eq. 4)}$$

Where, ν = kinematic viscosity (a function of water temperature)

B = channel width

Q = flow (ft^3/second)

Henderson and Bromage (1988) recommended that V_s not exceed 0.06 m/sec though preferably 0.017 m/sec. Warren-Hansen (1982) adopted more conservative guidelines of 0.02-0.04 m/sec.

Particle size studies by Boardman et al., (1998) indicated that the majority of particles in trout aquaculture sludge range from 5-20 µm (micrometers) in diameter. However, Cripps (1995) observed that significantly larger percentage of total particle volume was made up of larger particles (>60 µm), even though nutrient concentrations in smaller particles were greater. Maillard, et al. (in press) observed that the size of fish and type of farm activity influence particle size distributions. Boardman et al., (1998) also suggested that excessive sludge blanket development can lead to an increased V_s which, when exceeds the V_{scour} for settled sludge particles can result in resuspension and release to the receiving water body.

Understanding in-basin hydraulics is critical for validating basin designs 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). Mangelson and Watters (1972) and Pedahzur et al., (1993) observed through evaluating tracer data that the installation of baffles succeeded in increasing flow path lengths and mean retention times in stabilization basins. 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 methods 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).

Sedimentation is the most widely applicable and feasible way for removing solids and associated nutrients from flow-through trout farms (Hinshaw and Fornshell, 2002; Stechey, 1991; Summerfelt, 1998, MacMillan et al., 2003). However, the fact that solids are often stored within flow that eventually is discharged to receiving waters causes inherent practical problems associated with their operation. Cleanout of basins is time consuming, and can lead to infrequent cleanout routines. This can lead to degradation of solids particles which consume BOD and release dissolved nutrients (Clark et al., 1985; Westerman et al., 1993; Garcia-Ruiz and Hall, 1996; Phillips et al., 1993) and decreases particle sizes (Hinshaw and Fornshell, 2002; Maillard et al., in press). Laborious cleanout of large settling areas can result in particle resuspension. Cripps and Bergheim (2000) recommend sedimentation for localized pre-conditioning of wastes (quiescent zones), and for second stage dewatering of separated sludge as part of a multi-stage treatment approach.

1.1.3 Biofiltration

Dissolved nutrients compose a substantial portion of trout farm effluent loads that can not be removed by microscreens or sedimentation (Kelley et al., 1997). Biological treatment or filtration have been proven effective in recycling systems (Dumas and Bergheim, 2000; Schulz et al., 2003), though use in flow-through systems has been limited. Using aerobic bacteria (e.g. *Nitrosomonas* sp., and *Nitrobacter* sp.) growth for nitrogen removal and absorption of dissolved phosphorus by cyanobacteria, biological media filtration (biofiltration) is a potential treatment option for reducing nutrient concentrations in aquacultural effluents (Dumas et al., 1998, Bender et al., 2004). Bead filters or expandable granular biofilters, which provide substrate for bacteria and have efficient mechanical backwash capabilities, have been used for conditioning recirculating aquaculture systems. However, these systems have high capital costs, and create considerable head losses making them unsuitable for large effluent flows common in flow-through systems (Drennan et al., 1995). Sand filters have been evaluated by Kristiansen and Cripps (1996). Effective treatment of high-flow systems would require a sand filter equivalent to 40-70% of raceway surface area (Wong and Piedrahita, 2003). The use of wetlands for treating aquacultural effluents has been found to provide greater than 90% TSS, 20-70% N and 49-90% P removal through nutrient uptake by emergent plants (Adler et al., 1996; Schulz et al., 2003). Nutrient removal was negatively correlated with hydraulic retention times indicating wetlands may not be practical for high effluent flows.

The limitations of the biofiltration systems for flow-through aquaculture warrant the need for continued research into low cost alternatives that address dissolved nutrients in addition to particulate fractions. Aquamat® biofiltration media (Meridian Aquatic Technology, LLC., Calverton, MD) is a type of synthetic carpet-like substrate that hangs vertically in the water. Aquamats® exhibit a high effective surface area (200 m^2 per meter of material) (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) and enhance biological processes in ornamental ponds (Ennis and Bilawa, 2000). Further applications by Arndt et al. (2002) measured the enhancement fin growth in rainbow trout, when Aquamats® were configured within raceways, while Erler et al., (2004) quantified significant TSS and nutrient removal using Aquamats® in combination with omnivorous fish to treat shrimp farm effluent, given a considerable retention time, while Bratvold et al., (2000) observed decreases in ammonia levels using Aquamats® and sand sediment to treat shrimp farm wastewater. Aquamats® have also been widely used in municipal and agricultural wastewater treatment systems to provide media for submerged, attached growth biofilters (Westerman and Argo, 2002). These findings support further research of Aquamats® potential benefit for improving aquacultural effluents.

Aquamats® have potential for use in sedimentation basin receiving raceway effluent. Their vertical position in the water column can serve as a forgiving baffle that can buffer high surface flow-through velocities and reduce overall basin turbulence. This can to improve settling conditions and overall TSS removal. Once colonized by bacteria, they may also provide critical biofiltration which can not be achieved by sedimentation alone. Once installed, they would require little to no maintenance. This minimizes the overall operating costs associated with their application, which would be substantially higher with mechanical biofiltration systems (bead, sand filters) that require backwashing,

1.2 Literature Review: Characterization of Nutrient Leaching Rates from Settled Rainbow Trout (*Oncorhynchus mykiss*) Sludge.

Wastes from aquaculture include all materials used in the process of rearing aquatic animals which are not removed from the system. These include uneaten feed, excreta, chemicals and therapeutics, dead or escaped fish, and pathogens (Cripps and Bergheim, 2000). Historically in trout farm production, these wastes have been discharged to receiving waters by dilution as high flow effluents with low waste concentrations. In recent years, increased environmental regulation and the benefit of economies of scale has driven trout aquaculture to intensify production while reducing effluent flows and pollutant releases (Summerfelt and Wade, 1997; Viadero et al., in press). Waste management, specifically solids, has become an integral part of facility maintenance to reduce effluent loads (Seymour and Bergheim, 1991) and maintain adequate water quality in recirculating systems (Chen et al., 1994). To assist in designing effective solids removal protocols, information is needed to understand the composition of trout solids, rates of degradation, and the potential for nutrient leaching over time. This can help to provide a time frame for scheduling solids removal which minimizes pollutant contributions to receiving waters and reduces environmental stress on production stock.

1.2.1 Impacts of solids on fish and the environment

Solids accumulation in production raceways can result in declining water quality and have direct impact on fish health. Increased fin rot (Herbert and Merkens, 1961) and gill damage (Chapman et al. 1987; Bullock et al. 1994) in rainbow trout (*Oncorhynchus mykiss)* have been attributed to high suspended solids. Solids breakdown can occur due to prolonged exposure to shear forces and microbial digestion resulting in decreased particle size and increasing nutrient solubility (Clark et al., 1985). High levels of dissolved organic matter have been found to promote the growth of facultative pathogens affecting trout that are stressed by handling or high intensity rearing environments (Noble and Summerfelt, 1996). Nutrient and organic matter loading associated with solids generated from fish farms are also responsible for water impairments to receiving waters (Van Rijn et al. 1995; Boardman et al., 1998; Selong and Helfrich 1998; Kamps and Neill 1999; Fries and Bowles, 2002; VWRC, 2002).

1.2.2 Characteristics of trout sludge

Rainbow trout (*Oncorhynchus mykiss*) yield an 18-30% production of suspended solids and feces per unit of feed (Heinen et al., 1996, Bergheim et al., 1991, Beveridge et al., 1991). Additional suspended solids generation can result from overfeeding which has been averaged as 150-200 g/kg feed (Cho et al., 1991; Cripps and Bergheim, 2000). Combined, 50% or more of feed by weight can ultimately result in suspended solids that accumulate in raceways or are lost to receiving waters (Summerfelt, 1999). Improved feeding techniques (Juell, et al, 1993; Mayer and McLean, 1995; Thorpe and Cho, 1995l Zhu et al., 2001) can reduce solids generation from waste feeding. However, solids production of 30-50% of daily feed input is common even with a feed conversion ratio (kg feed: kg fish gain) of 0.9-1.0 (Cripps and Bergheim, 2000).

Studies have been conducted to characterize the nutrient composition of trout solids. Relative to total effluent loads, reported filterable or settleable solids contain 30-80% of the effluent phosphorus (P) but only 15-32% of the total nitrogen (N) in effluent (Heinen et al., 1996; Foy and Rosell, 1991; Bergheim et al., 1993). Axler et al. (1997) evaluated trout solids that had accumulated over a two week period and found that the nitrogen to phosphorus ratio

(N:P) ranged from 1.1-3.1. Naylor et al. (1999) defined a N:P ratio closer to 1.0 after evaluating solids from 12 commercial rainbow trout farms in Canada. Both studies indicate that waste solids are enriched in phosphorus relative to nitrogen given typical feed N:P ratios that range from 4-7 (Gatlin and Hardy, 2002).

1.2.3 Nutrient leaching from sludge

Research by Garcia-Ruiz and Hall (1996) found that the leaching of labile phosphorus from manually extruded rainbow trout feces was greater than that from feed, despite the phosphorus concentration in the feed being twice as high. They reported that phosphorus leaching from both feed and feces was rapid; the majority being leached within 5-24 h. Additional leaching after 24 h was minimal with and without the inhibition of microbial activity by formaldehyde. However, with microbes present soluble reactive phosphorus or *ortho*-phosphates were readily assimilated to bacterial biomass.

Phillips et al. (1993) evaluated leachate that was immediately screened through feed and manually extruded fecal pellets of Atlantic salmon. They found that dissolved reactive phosphorus (DRP) was abundant in feed pellet leachate, while particulate phosphorus (PP) formed the greater portion of fecal leachate. The study concluded that up to 10% of the total phosphorus effluent load could be attributed to immediate leaching occurring within the first 600 seconds after deification.

Further research has shown that nutrient release and solids degradation of naturally settled trout solids could occur over much longer periods (weeks and months). The biochemical oxygen demand (BOD) of rainbow trout feed and sludge was investigated by Mathieu and Timmons (1993). Their research indicated that the BOD of both feed and solids would continue to increase well beyond 5 days, and therefore recommended solids removal be performed within this time period, especially in closed systems. Westerman et al., (1993) found the nutrient concentration of solids collected from settling areas in flow-through systems decreased with increasing age when comparing solids < 2 weeks old to solids aging from 1-9 months.

In summary, the current understanding of solids leaching acknowledges that rapid nutrient release occurs over short time periods (up to 24 hours). The extent of leaching over longer periods is not well defined. This warrants continued research to fully understand and quantify the overall leaching potential of settled solids. Defining this will help to guide aquaculture facility maintenance schedules, which often are often dictated by allowable labor costs rather than by contributions to pollutant loads.

Chapter 2: Treatment of Rainbow Trout (Oncorhynchus mykiss) Raceway Effluent Using Baffled Sedimentation and Artificial Substrates

2.1 Introduction

Impaired water quality in streams supply 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 operators are adopting best management practices to improved 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., in press) 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 et al., 1991; Boardman, et al., 1998; IDEQ 1998).

Reported concentration ranges for trout effluent variables 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 found that the majority of nitrogen, phosphorus and organic carbon released from studied trout farms is sediment bound (VWRC, 2002). Others suggest a large variation in particulate nutrient fractions, ranging from 30-80% 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).

2.1.1 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 (2678-14170 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 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 Division 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 2.0-5.0 cm/sec (0.066-0.164 ft/sec), while smaller particles broken down by biodegradation and turbulence settle at much slower rates, ranging from 0.046-0.122 cm/sec (0.0015-0.0030 ft/sec) (IDEQ, 1998). Wong and Piedrahita (2003) estimated the settling velocity for settleable solids in trout effluent as 1.7 cm/sec (0.056 ft/sec). Warren-Hansen (1982) observed the average settling velocity of solids in trout effluent ranged from 1.7-5.0 cm/sec (0.05-0.14 ft/sec). 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 5-20 μm in diameter. This size corresponds with a minimum scouring velocity 0.20-0.40 m/sec. Hence, the horizontal velocity within the basin must not exceed this rate to prevent scouring.

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).

2.1.2 Biofiltration

The dissolved nutrient fractions in trout farm effluent is 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 meter 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, given a considerable retention time, while Bratvold et al., (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.

2.2 Methods and materials

2.2.1 Study site

Four, consecutive production raceways 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 (6,681 m^3/day, 10 yr 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.

2.2.2 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 x 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 x 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 (15ft x 3ft) 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 on 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.

2.2.3 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 (4,000 ft^2) of effective surface area. In total, 12 Aquamat® units were installed within the first section of the basin providing roughly 4,400 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.

2.2.4 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 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).

2.2.5 Flow monitoring

Flow measurements were made at the rectangular outfall of production raceway #2. Using the Francis formula for sharp-crested weirs (Wood, 1974, pp. 75), water depth measurements were converted to flow (m^3/day) across the 2.44 m wide weir. Based on nine years of historical flow data, a time-weighted average flow of 6,681 m^3/day (1,226 gal./min) was determined.

2.2.6 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).

2.3 Results

2.3.1 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%).

Removals of TP and TAN increased with increasing basin volume as 18% TP and 12% TAN 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 concentrations during normal operation conditions were generally low (2.7-4.8 mg/L TSS).

2.3.2 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% and 16% TAN and 12% and 17% nitrite 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.

2.3.3 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 a calculated retention times were 72 min with Aquamats® and 82 min without 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 min and 29 min, respectively for the first section. For the total basin, V_O averaged 19.1 m^3/m^2-day 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 4,550-5,762 m^3/day, horizontal flow-through velocities ranged from 0.009-0.014 m/sec at the widest channel sections (6.1 m) and 0.036-0.057 m/sec at the 1.5 m baffle openings. These velocities were well below the minimum scouring velocities (0.2-0.4 m/sec) necessary to cause resuspension of 5-20 µm settled particles.

2.4 Discussion

2.4.1 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 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 2/25/05 averaged 0.60 mg/L and resulted in a 70% removal at station 5, while on 1/10/05, 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 (≤ 2 mg/L) even during higher loading conditions. Of the 23 grab samples collected during cleaning and harvesting conditions, 7 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), first section of the basin was still responsible for 84% of overall removal of solids, 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 expected 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, longer retention time of the large sedimentation basin (51-66 min) and resulting low V_O (11.8 – 21.2 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.

2.4.2 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 days to achieve sufficient solids and nutrient removal (Westerman et al., 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.

2.4.3 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 Michelson (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 Laio (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.

2.5 Conclusion

- The baffled sedimentation basin receiving rainbow trout (*Oncorhynchus 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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2.8 Figures

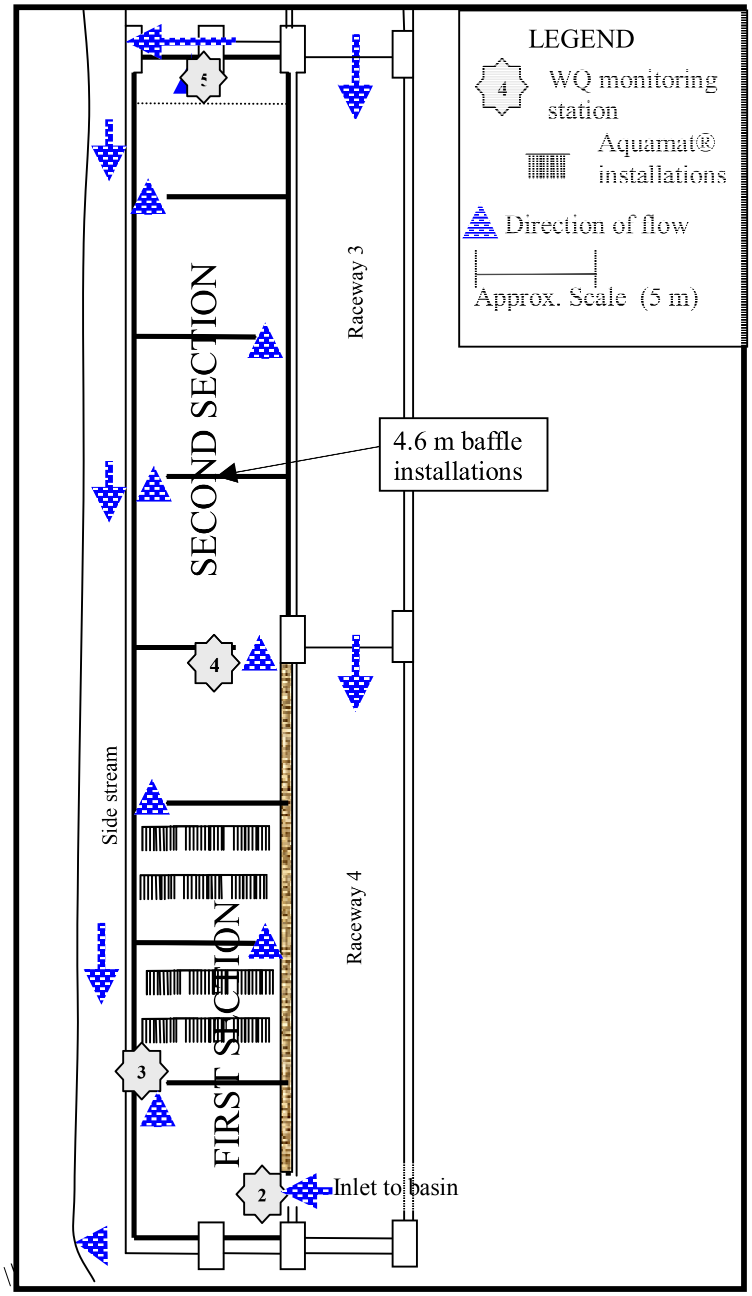

Fig. 1. Plan view of raceways and sedimentation basin

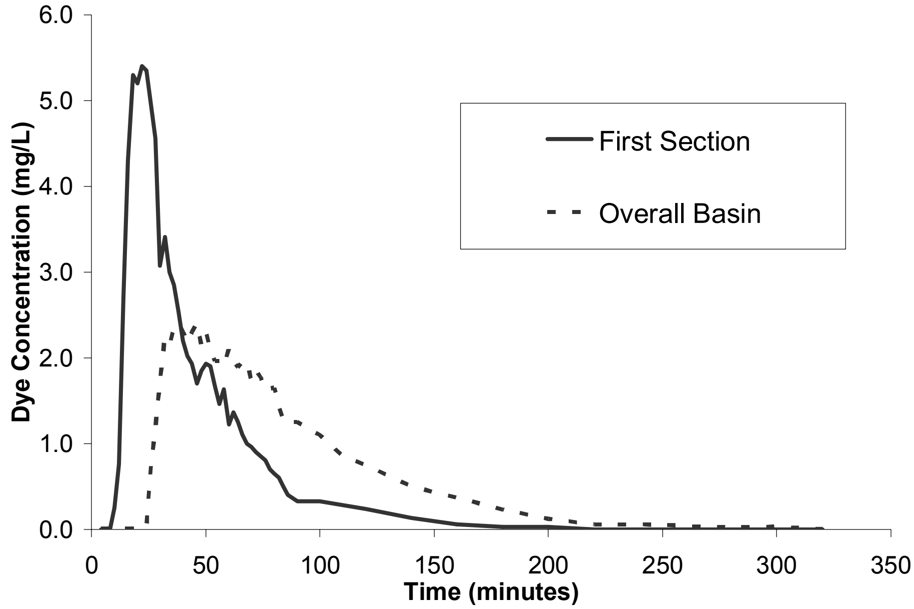

Fig. 2. Tracer dye concentrations versus time, Aquamats® installed.

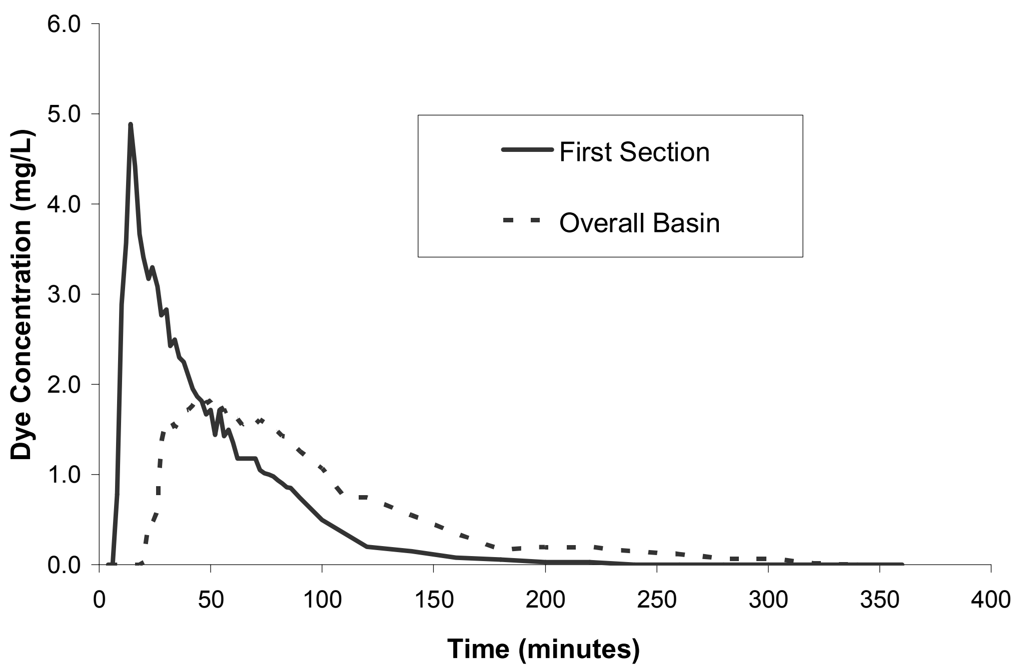

Fig. 3. Tracer dye concentrations versus time, Aquamats® removed.

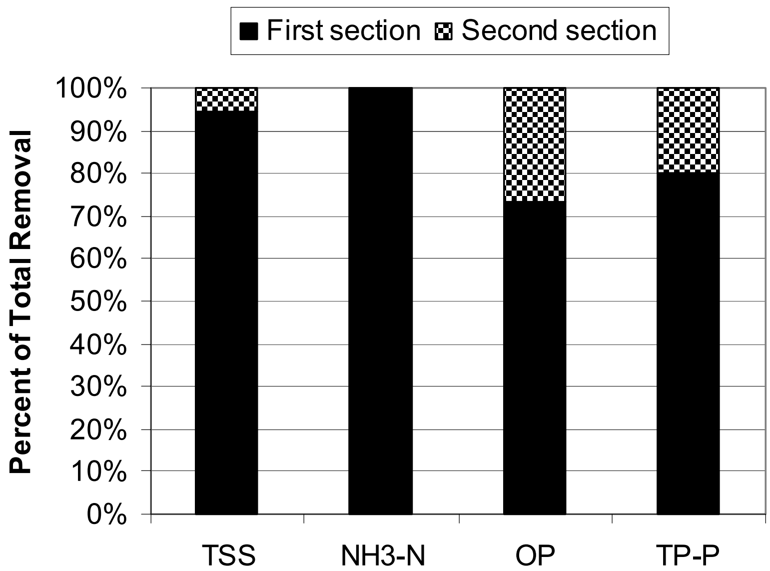

Fig. 4. Removal contributions by section during cleaning and harvesting activities

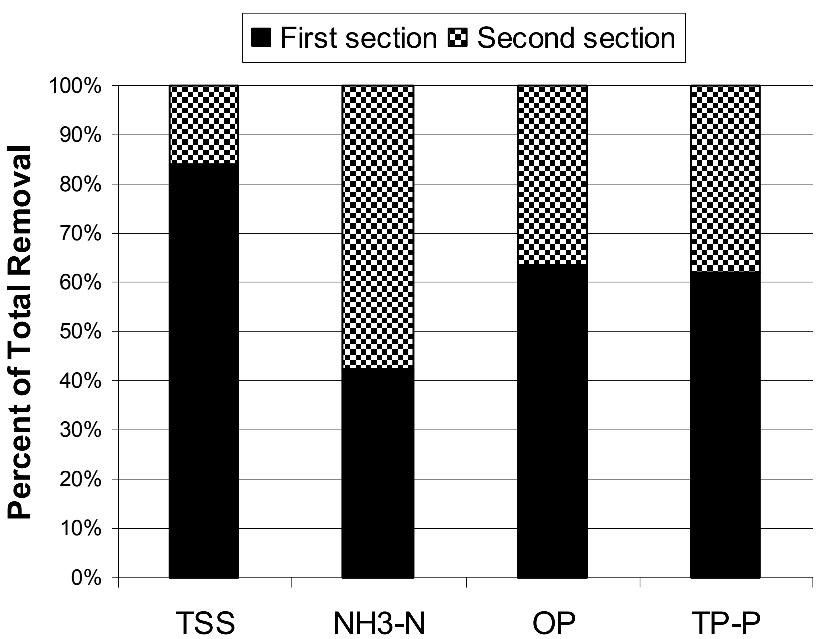

Fig. 5. Removal contributions by section during normal operations

2.9 Tables

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	NO_2	OP[1]	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	<.02		0.04-0.70[3]
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 et al., 1991	6.8-9.4	5.4-14.3	<1 – 9		0.02-0.89	0.1-2.4[2]			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., in press		7.3-10.4	4-12		0.10-0.36				

[1] Orthophosphate (OP)
[2] value for nitrate + nitrite
[3] value for total phosphates

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, 1981	less 57.6 m^3/m^2-day (189 ft^3/ft^2-day)

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

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,e]
Total Organic Carbon – TOC (as C)	persulfate-ultraviolet oxidation method 5310 C[a,e], Dohmann DC-80 TOC analyzer by Rosemount Analytical, Inc.
Total Ammonia Nitrogen - TAN (as N)	Salycilicate method, Hach® Method 8155[b,c,d]
Nitrite – NO_2 (NO_2-N)	Dianozation method, Hach® Method 8155[b,c,e]
Nitrate – NO_3 (NO_3-N)	Cadmium reduction method, Hach® Method 8155[b,c]
Orthophosphate – OP (PO_4-P)	Ascorbic acid method, Hach® Method 8048[a,b,e]
Total Phosphorus – TP (PO_4-P)	Acid persulfate digestion, Ascorbic acid detection method, Hach® Method 8190[a,b,e]
Dissolved Oxygen – DO (as O)	YSI, Inc. Dissolved Oxygen/Temperature meter

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

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

Table 6. Average removal efficiency under normal operation loading.

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

* all values in mg/L
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**	**.03**	**1.47**	**0.25**	**0.33**
	3	**56%**	**6%**	**15%**	**8%**	**-20%**	**21%**	**34%**
	n	3	3	3	3	3	3	3
	4	**89%**	**12%**	**9%**	**8%**	**-1%**	**37%**	**53%**
	n	3	3	3	3	3	3	3
	5	**92%**	**20%**	**0%**	**-3%**	**14%**	**42%**	**55%**
	n	3	3	3	3	3	3	3
				Aquamats® Removed				
Ave. Influent WQ*	**2**	**12.2**	**1.08**	**0.26**	**0.01**	**1.51**	**0.28**	**0.48**
	4	**73%**	**-3%**	**17%**	**12%**	**5%**	**26%**	**39%**
	n	3	2	3	3	3	3	2
	5	**79%**	**-4%**	**16%**	**17%**	**-11%**	**46%**	**61%**
	n	3	2	3	3	3	3	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.

Table 8. Sedimentation basin hydraulic characteristics.

Parameter	Result	
	First Section (Sta. 4)	**Total Basin (Sta. 5)**
During tracer study (Q = 3,623 m^3/day)		
Theoretical ret. time (V/Q)	54 min	99 min
Calc. ret. time – Aquamats® installed	34 min	72 min
Calc. ret. time – Aquamats® removed	37 min	82 min
% dead space – Aquamats® installed	37 %	27 %
% dead space – Aquamats® removed	32 %	17 %
During WQ monitoring		
Adj. overflow rates: Aquamats® installed	44.1 m^3/m^2-day	19.1 m^3/m^2-day
Adj. overflow rates: Aquamats® removed	35.8 m^3/m^2-day	14.8 m^3/m^2-day

Table 9. Comparison of pollutant loads versus production stocking density

Month	Ave. Stock (kg)	Average Production Effluent Concentrations (mg/L) N	TSS	TAN	NO_3	OP	TP
June-04	10684	2	8.6	0.58	1.6	0.17	*
July-04	10973	3	2.2	0.41	2.0	0.12	0.13
Aug-04	15612	2	3.1	0.24	1.7	0.14	0.14
Dec-04	22334	6	6.2	0.43	1.3	0.16	0.20
Jan-04	23658	1	4.8	0.35	1.9	0.12	0.13
April-04	1110	1	1.3	0.22	0.8	0.06	0.08
June-05	7672	1	4.4	0.18	0.5	0.06	0.07

* TP not analyzed

Chapter 3: Characterization of Nutrient Leaching Rates from Settled Rainbow Trout (*Oncorhynchus mykiss*) Sludge.

3.1 Introduction

Solids management is integral in maintaining effluent water quality standards for aquacultural facilities. Sludge accumulation in raceways can result in declining water quality and directly impacting fish production (Herbert and Merkens 1961; Chapman et al. 1987; Bullock et al. 1994). Nutrients and organic matter associated with solids generated from fish farms can pollute receiving waters (Van Rijn et al., 1995; Selong and Helfrich, 1998; Kamps and Neill, 1999; Fries and Bowles, 2002). To design effective solids removal protocols, an understanding of trout sludge composition, degradation and potential leaching of nutrients is needed. Nutrient leaching rates are important for establishing cleaning rates to minimize downstream eutrophication.

Rainbow trout (*Oncorhynchus mykiss*) yield an 18-30% production of suspended solids and feces per unit of feed (Bergheim et al., 1991, Beveridge et al., 1991, Heinen et al., 1996). Additional suspended solids generation can result from overfeeding and average between 150 and 200 g/kg feed (Cho et al., 1994; Cripps and Bergheim, 2000). As much as 50% or more of feed fed (by weight) can result in waste high in suspended solids that accumulate in raceways and downstream (Summerfelt, 1999). Settleble solids in trout facilities contain 30-80% of the effluent phosphorus (P), and 15-32% of the total nitrogen (N) in effluent (Heinen et al., 1996; Foy and Rosell, 1991; Bergheim et al., 1993). Axler et al. (1997) found that the nitrogen to phosphorus ratio (N:P) in trout sludge ranged from 1.1-3.1, where as Naylor et al. (1999) found the N:P ratio to be near 1.0 in rainbow trout farms in Canada. Trout sludges are enriched in phosphorus, given typical feed N:P ratios that range from 4-7 (Gatlin and Hardy, 2002).

Garcia-Ruiz and Hall (1996) suggested leaching of phosphorus from trout feed and feces was rapid, with the majority being leached within 24 h. Phillips et al., 1993 observed that leachate from Atlantic salmon feed was dominated by dissolved reactive phosphorus (DRP), while particulate phosphorus (PP) formed the greater portion of fecal leachate, and that as much as 10% of the total phosphorus leached was released within the first 10 min. Though rapid leaching has been documented, additional research is needed to confirm rates and lengths of active leaching from sludge.

This study assesses amount of rapid leaching (within 24) relative to the total amount of leaching occurring over a 7 day period. A comparison was made between undisturbed sludge and sludge receiving agitation and aeration. When applicable, leaching rates were determined. This information is important for recognizing cleaning schedules that minimize reductions in effluent quality.

3.2 Methods and materials

3.2.1 Trout sludge collection

Trout sludge used for this study was collected from the quiescent zone of a production raceway rearing rainbow trout at Cast-a-line Trout Farms in Craigsville, Virginia. The average age of the sludge was determined to be 3.5 days, since cleanout of the quiescent zone occurred 7 days prior. Most of the sludge collected existed as intact fecal pellets with little degradation. The sludge was removed using a fine mesh scoop, drained of water, placed in a clean plastic bucket, and transported back to Virginia Tech for analysis. The sludge was analyzed for total solids (TS) using standard methods (APHA, 1998) and various nutrient parameters (Section 2.2).

3.2.2 Nutrient leaching experiments

Two L of sludge were added to each of two square polycarbonate tanks (A and B) in a temperature controlled room at 20 degrees C. Eighteen L of deionized water were slowly added to each tank to minimize resuspension of the settled sludge. Tank A was not agitated, and simulated conditions in the quiescent zones of sedimentation basins or raceways, where turbulence generated by fish or high flow-through velocities were restricted. Two 10 cm air stones were installed in tank B to provide circulation and agitation of the settled sludge simulating fish movement in fully stocked production raceways.

Once the tanks were filled, an immediate water sample provided the initial baseline nutrient concentrations in the overlying water, for subsequent comparison. All samples were analyzed within 12 h of collection, or frozen for analysis within 7 days. Sampling frequency and nutrient parameters analyzed are presented in Tables 1 and 2. Aeration was eliminated 30 min prior to sampling. Samples were extracted with a 50 ml pipette at 15 cm depth to represent the average water quality within the tank and prevent settled solids or surface scum from entering the sample. After sampling, aeration was resumed.

Nutrient concentrations were plotted versus time and evaluated using linear and power regression equations. Average leaching rates in mg/g solid-h over the 24 hour period for each nutrient were obtained using Eq.1. Volume used in the equation accounted for sample volume removed from each tank.

$$\text{24-hour average leaching rate (mg/g-h)} = \frac{Slope \times Volume}{144.2g} \qquad \text{(Eq. 1)}$$

Slope, of linear regression (concentration increase per hour)
L, liters (average total) of water in tank
g, grams of sludge (total dry wt.) added to each tank
Volume, 19.5 L (0-24h), 18.65 L (days 2-7)

To calculate a rate increase for a specific time period using power regression equations, the value for hours in the denominator ranged from 0-24. Varying the hour value accounts for the continually changing rate of increased observed during this period. In contrast, linear equations described herein represent a per hour rate that is constant over a specific monitoring period.

3.3 Results

3.3.1 Sludge characteristics

Trout sludge is characterized in Table 3. Based on TS concentration (7.21 g/L), 144.2 g (dry wt) of trout sludge was added to each tank as 2 L of wet sludge. Given a 3.52% P and 3.02% N dry solids content (Table 3), 4.81 g P and 4.36 g N was added to each tank. The sludge N:P ratio of 0.91 was within expected ranges published for trout sludge (Westerman et al., 1993; Axler et al., 1997; Naylor et al., 1999).

3.3.2 24 h nutrient leaching

Samples collected within 24 h of monitoring revealed that TP, OP, TKN and TAN concentrations in the overlying water quickly increased (Figs. 1 and 2). Nutrient leaching occurred most rapidly in tank B (agitated and aerated). OP increased following a power regression of 12.2 mg-$h^{0.27}$ /L (R = 0.997) in tank B (Fig. 1). OP concentrations in tank A increased linearly at a rate of 0.491 mg/L-h (R = 0.959) (Fig. 2). TP concentrations in tank B increased according to a power regression of 13.0 mg-$h^{0.250}$/L (R = 0.999), whereas TP in tank A increased linearly at 0.483 mg/L-h (R = 0.957) (Fig. 2). TKN in tank B increased at the rate of 17.1 mg-$h^{0.216}$/L (R = 0.999), as compared to a linear increase observed in tank A which averaged 0.547 mg/L-h (R = 0.990) (Fig. 3). TAN increases in Tank B followed the power regression equation 3.93 mg-$h^{0.285}$, whereas TAN in tank A increased linearly at a rate of 0.311 mg/L-h (R = 0.972) (Fig. 4). TOC in tank B increased at a rate of 108 mg-$h^{0.459}$/L (R = 0.988) in tank B, and linearly at 8.57 mg/L-h (R = 0.927) in tank A (Fig. 5). The maximum TOC (457 mg/L) tank B occurred during the 24^{th} h. Nitrate and nitrite concentrations varied widely and were not evaluated.

Average nutrient leaching rates for OP, TP, TKN, TAN and TOC were determined for Tank A, using observed linear increases (Table 4). Non-linear, concentration increases in tank B are not reported in Table 4, as the leaching rate changed continuously throughout the period. The power regressions indicate the highest leaching rates occurred within the first 8 h.

3.3.3 2-7 day nutrient leaching

Marked differences in nutrient leaching rates occurred between tanks A and B during days 2-7. A continual linear TP increase of 0.196 mg/L-h was observed in tank A while TP decreases after 60 h (2.5 days) and continued to decline steadily through day 7 in tank B (Fig. 6). OP and TKN concentrations decreased in tank B, whereas TAN leveled off after 60 h (Fig. 7). TOC concentrations in tank B decreased continually after day 1 (Fig. 8).

Dissolved nutrient and organic matter levels declined in tank B probably by bacterial assimilation which may have masked any additional leaching of nutrients from the trout sludge. Chemical precipitation also may have occurred due to high concentrations in the tank and oxygen presence. A suspended floc developed in tank B, and settled as a grayish layer over the brownish trout sludge on the bottom of the tank. The resulting non-linear nutrient fluctuations in tank B prevented the calculation of leaching rates.

Nutrient concentrations in tank A continually increased during days 2-7, though at a slower rate than in the first 24 h (Fig. 9). TOC in tank A declined steadily from 24-60 h before increasing to a maximum concentration of 456 mg/L at day 7 (Fig. 8). TOC concentration increased at 2.38 mg/L-h ($R = 0.862$). Average nutrient leaching rates were determined for days 2-7 based on linear relationships (Table 4).

Microbial uptake of nutrients in tank A did not limit concentration increases, as linear relationships were continuous for all parameters, with the exception of nitrate and nitrite. Dissolved oxygen (DO) was likely the limiting factor controlling microbial growth, as DO measured < 1 mg/L after day 1. Consequently, low DO may also suggest that anaerobic digestion of sludge could have contributed to additional leaching. DO measurements in tank B were typically above 5 mg/L.

3.4 Discussion

3.4.1 24-h nutrient leaching

The leaching of nutrients from trout sludge during the first 24 h of monitoring was considerable in both tanks. In tank A, 35% of TP, 35% of OP, 61% of TKN, 24% of TAN, and 50% of TOC leached over 7 days, occurred in the first 24 h of monitoring (Fig. 10). In tank B, higher percentages were observed as 83%, 84%, 78%, 40% and 100% of the total TP, OP, TKN, TAN, and TOC leached occurred during the first 24 h. However, percentages for tank B are likely inflated given concentration decreases from days 2-7.

Calculated 24 hr nutrient leaching rates were much higher than average rates determined for days 2-7. In tank A, the leaching rate for TP was 2.6 times higher during the first 24 h (0.065 mg/g-h) than that observed during days 2-7 (0.025 mg/g-h). For TKN, the 24 hour leaching rate (0.074 mg/g-h) was almost 11 times higher than the 2-7 day rate (0.007 mg/g-h).

Agitation and aeration occurring in tank B accelerated the leaching of nutrients and organic carbon within the first 24 hours of deposition. TOC increased from 37-254 mg/L in tank A (no agitation), while in tank B (with agitation) TOC increased from 57- 439 mg/L during the first 20 h. Mixing and turbulence created by the air stones likely promoted the breakdown of large fecal pellets and release of dissolved nutrients indicating the use of quiescent zones at the end of trout raceways isolated from fish to remove solids will reduce sludge breakdown and nutrient release. The rapid (24 h) leaching observed emphasizes the importance of expediently (daily) removing sludge from production raceways and settling basins on a frequent or continuous basis, as suggested by Mathieu and Timmons (1993). Weekly (MacMillan et al., 2003) or biweekly IDEQ (1998) cleanout schedules have been previously recommended.

3.4.2 2-7 day nutrient leaching

Although cumulative leaching of nutrients during days 2-7 occurred at a slower rate, the prolonged release is substantial. In tank A, 65% of TP, 65% of OP, 39% of TKN, 76% of TAN, and 55% of the total TOC leached, occurred during days 2-7 (Fig. 10). Therefore, daily removal of solids from raceways or settling areas would prevent this additional pollution to effluent or recirculating flow.

Declining nutrient concentration in Tank B during this period suggest that the majority of leaching, with the exception of TAN occurred during the first 24 h. However, it is more likely that leaching continued in Tank B, but observed concentrations were limited by bacterial uptake and/or chemical precipitation. Eventual bacterial die-off and cellular degradation could result in a subsequent release of dissolved nutrients, as suggested by Garcia-Ruiz and Hall (1996).

Evidence of significant leaching after 24 h differ from data reported of Garcia-Ruiz and Hall (1996). These findings are reasonable considering trout sludge continues to generate biochemical oxygen demand (BOD) beyond 5 days (Mathieu and Timmons, 1993), and that older trout sludge (1-9 months) has lower N and P concentrations than younger sludges (< than 2 weeks) (Westerman et al., 1993). Prolonged nutrient leaching also builds upon the findings of Phillips et al. (1993), who did not include leaching of settled sludge on the lake bottom, when predicting phosphorus loadings to lakes by caged trout occurred as feed and fecal pellets sank through 30 m water depths.

Constant leaching of phosphorus, nitrogen and organic carbon (Figs. 5, 7 and 8) in tank A suggest that leaching will continued well beyond 7 days from settled trout sludge. Therefore even higher percentages of total leaching could exist after the first 24 h, if settled sludge remains in flow for extended time periods.

Controlling phosphorus and nitrogen export from trout sludge is a major regulatory problem in aquaculture. Heinen et al. (1996) observed the phosphorus concentration in settleable solids was higher in when trout were fed high energy feeds versus low energy feeds. Flimlin et al. (2003) observed the P content in trout fecal matter was a function of indigestible P, as commercial feeds fish meal and soybean meal resulted in higher fecal P. Regardless of feed nutrient content, the frequency of sludge removal from raceway or settling basins is a critical management strategy for limiting nutrient pollution from trout farms.

3.5 Conclusion

- Leaching of nutrients from settled rainbow trout (*Oncorhynchus mykiss*) sludge occurred continually through 7 days.
- Highest leaching rates occurred during day 1 in both a stagnant (tank A) and an agitated and aerated tank (tank B).
- Linear regression equations accurately described concentration increases of TP, OP, TKN, TAN, and TOC during the first 24 h in tank A, while power regressions described concentration increases of these parameters in tank B.
- These findings indicate the use of quiescent zones at the end of trout raceways isolated from fish to remove solids will reduce sludge breakdown and nutrient release.
- Aerobic microbial uptake of dissolved nutrients and/or chemical precipitation may have been responsible for decreasing TP, OP, TKN, TAN and TOC concentrations in tank B during days 2-7.
- Continual, linear increases in TP, OP, TKN, TAN and TOC occurred in tank A during days 2-7 accounting for a 39-76% of total observed leaching, and suggest that nutrient release will continue beyond 7 days,.
- Compared to weekly cleaning (7 days), daily solids removal from raceways and settling areas could reduce nutrient leaching by 65% for TP, 65% for OP, 39% for TKN, 76% for TAN, and 55% for TOC.

These findings aim to improve our understanding of nutrient releases from trout sludge. As well, this information is useful for justifying the implementation of best management practices and effective schedules for removing accumulated sludge from production raceways and settling areas.

3.6 Acknowledgements

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3.8 Tables

Table 1. Schedule of sample collection

Day	Number of samples	Time interval
1	7	Every 4 h
2	3	Every 8 h
3-7	2	Every 12 h

Table 2. Water quality parameters and associated methodology used for analysis

Parameter	Methodology
Total Phosphorus – TP (PO_4-P)	Acid persulfate digestion, Standard Method 4500-P F[a]
Ortho-phosphate – OP (PO_4-P)	Acid persulfate digestion, Ascorbic acid detection method, Hach® Method 8190[a,b,e]
Total Ammonia Nitrogen - TAN (as N)	Salycilicate method, Hach® Method 8155[b,c,d]
Nitrite – NO_2 (NO_2-N)	Dianozation method, Hach® Method 8155[b,c,e]
Nitrate – NO_3 (NO_3-N)	Cadmium reduction method, Hach® Method 8155[b,c]
Total Kjeldahl Nitrogen – TKN (as N)	Block digestion and flow injection analysis, Standard Method 4500-N D[a]
pH	w/electrosylicate pH probe

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

Table 3. Characteristics of trout sludge

Parameter	**Value**	**% of solids (per gram sludge dry wt.)**
Total solids	7.21 g/L	7.21%
Total phosphorus (TP)	2540 mg/L (PO_4-P)	3.52%
Ortho-phosphate (OP	306 mg/L (PO_4-P)	0.42%
Total Kjeldahl Nitrogen (TKN)	2100 mg/L (as N)	2.91%
Total ammonia nitrogen (TAN)	411 mg/L (as N)	0.57%
Nitrite (NO_2)	2.62 mg/L (NO_2-N)	< 0.01%
Nitrate (NO_3)	66.7 mg/L (NO_3-N)	0.11%
Total Nitrogen (TN)	2180 mg/L (as N)	3.02%
Total organic carbon (TOC)	3640 mg/L (as C)	5.05%

Table 4. Tank A average rate of increase for nutrient concentrations and nutrient leaching rates (mg/g sludge-h) from trout sludge for the period 24 hours and days 2-7.

Nutrient parameter	**Average rate of concentration increase**	**Rate of nutrient leaching from sludge**
	mg/L-h	**(mg leached)/(g solid-h)**
24 h leaching rates		
TP	0.483	0.065
OP	0.492	0.066
TKN	0.547	0.074
TAN	0.311	0.042
TOC*	8.57	1.16
2-7 day leaching rates		
TP	0.196	0.025
OP	0.157	0.020
TKN	0.051	0.007
TAN	0.164	0.021
TOC*	2.38	0.308

* rates based on observed concentrations during days 2.5-7

3.9 Figures

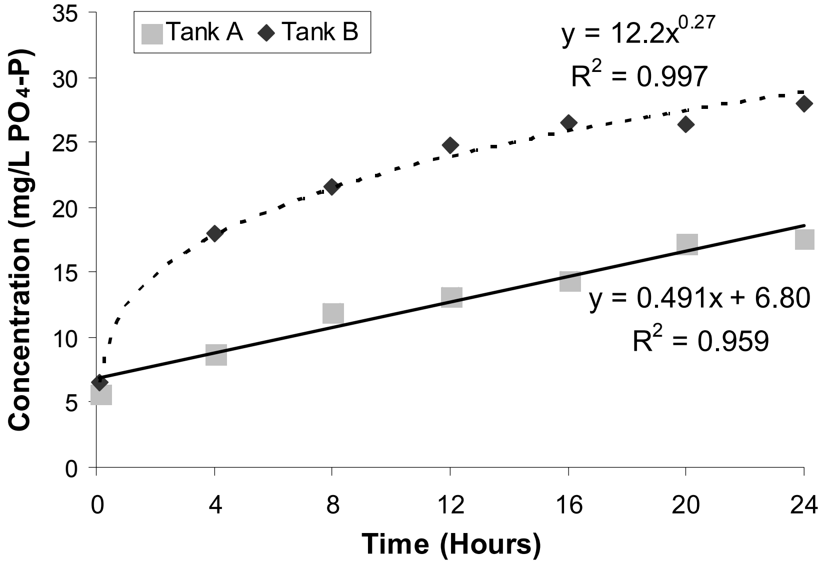

Fig. 1. *Ortho*-phosphate (OP) concentrations within 24 h (tanks A and B).

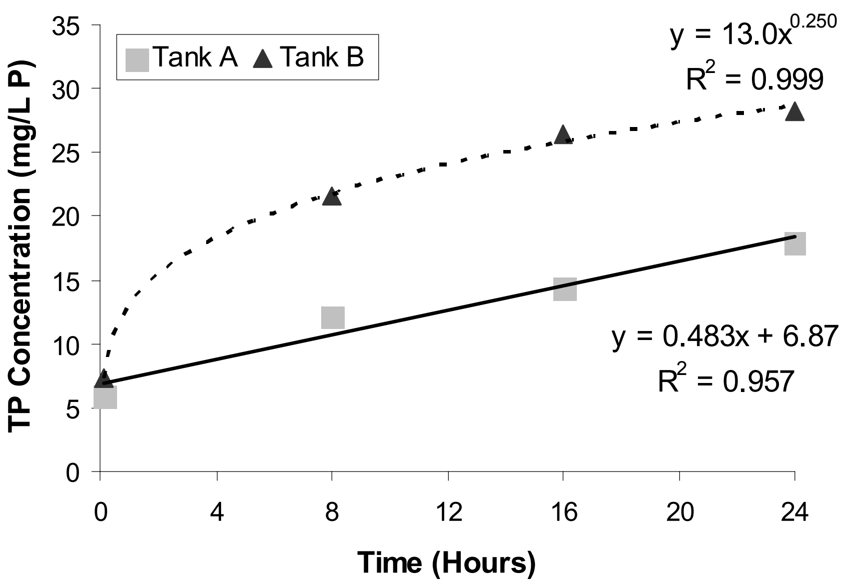

Fig. 2. Total phosphorus (TP) concentrations over 24 h (tanks A and B).

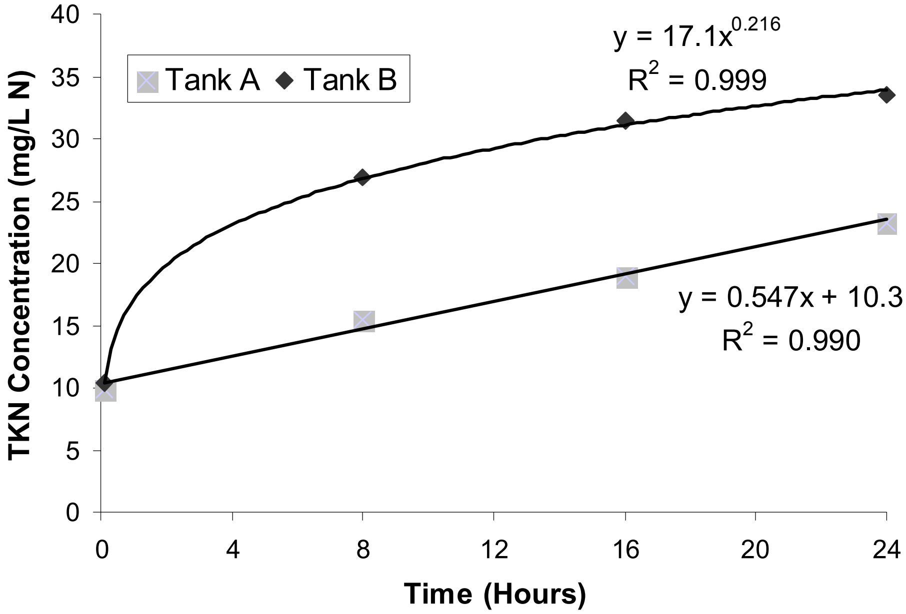

Fig. 3. Total Kjeldahl nitrogen (TKN) concentrations over 24 h (tanks A and B).

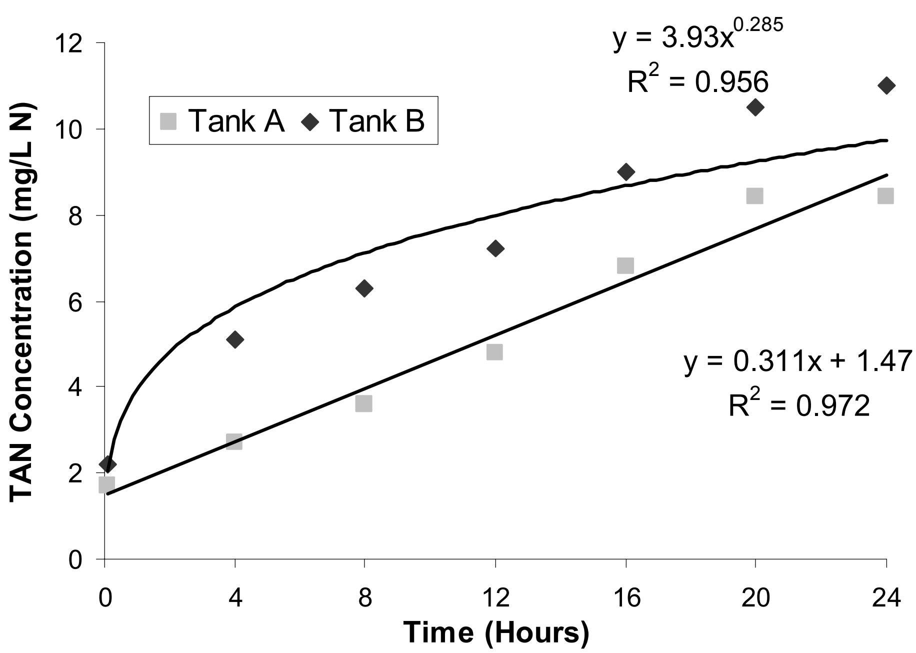

Fig. 4. Total ammonia nitrogen (TAN) concentrations over 24 h (tanks A and B).

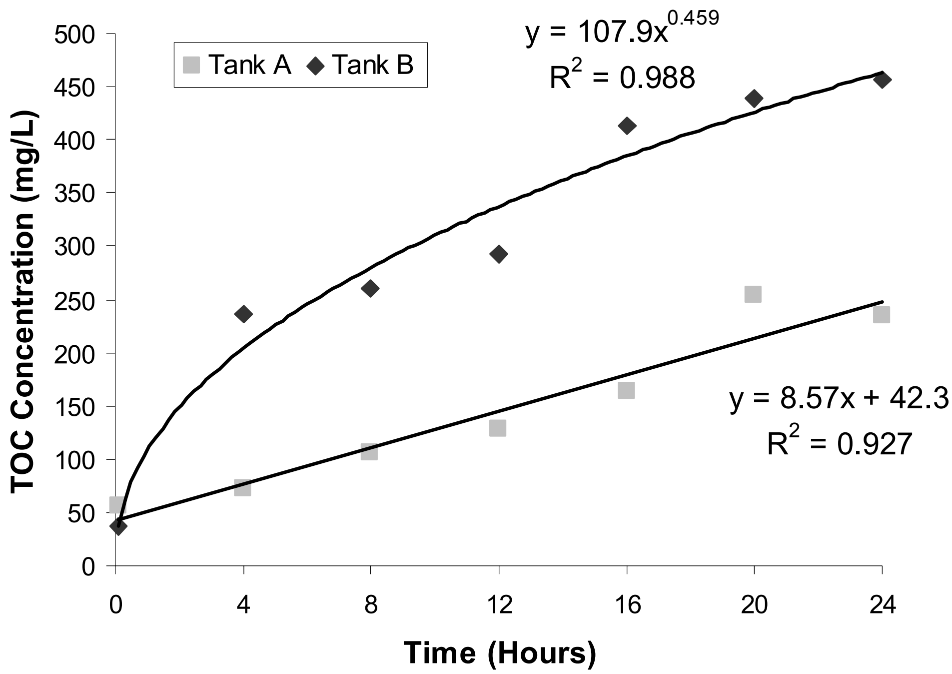

Fig. 5. Total organic carbon (TOC) concentrations over 24 h (tanks A and B).

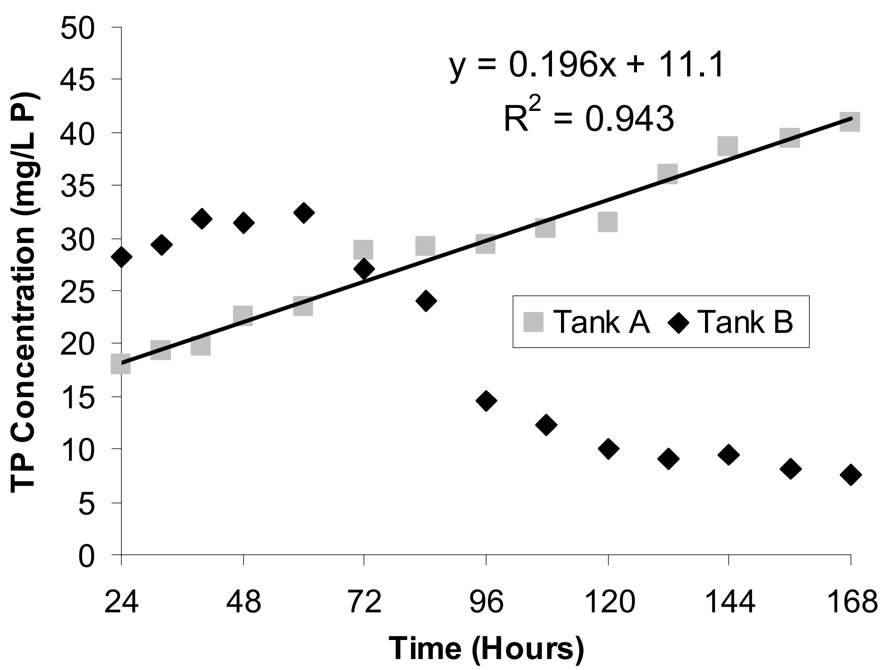

Fig. 6. Total phosphorus (TP) concentrations observed from day 2-7 (tanks A and B).

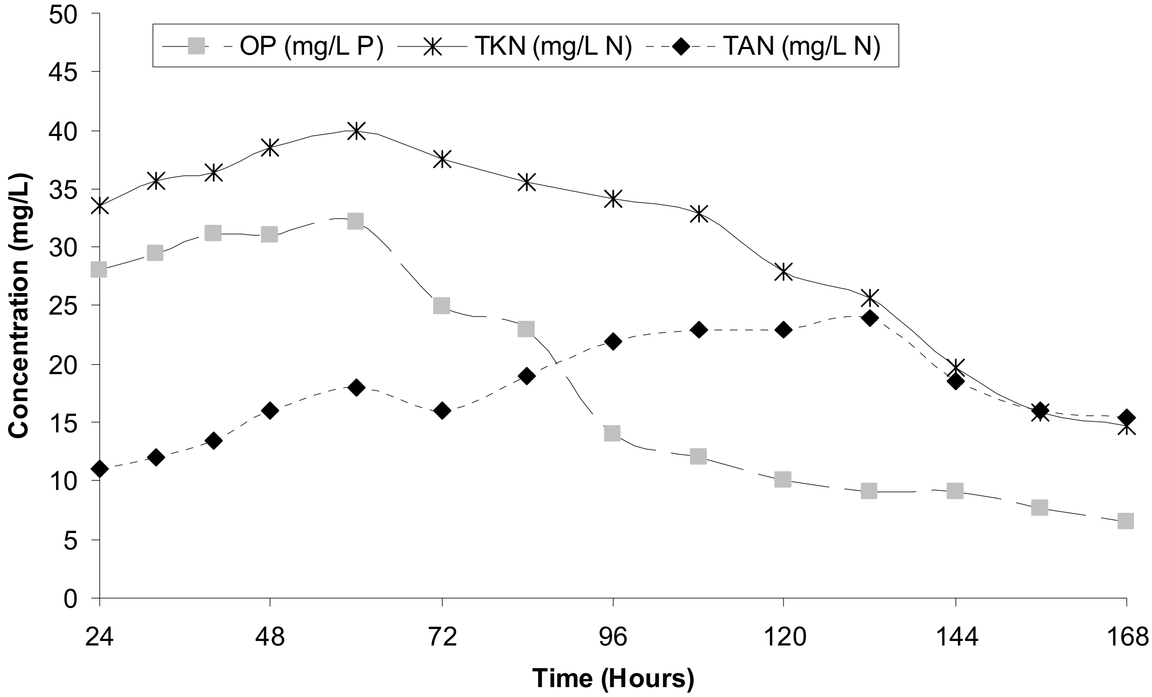

Fig. 7. *Ortho*-phosphate (OP), total Kjeldahl nitrogen (TKN), and total ammonia nitrogen (TAN) concentrations in tank B observed from day 2-7.

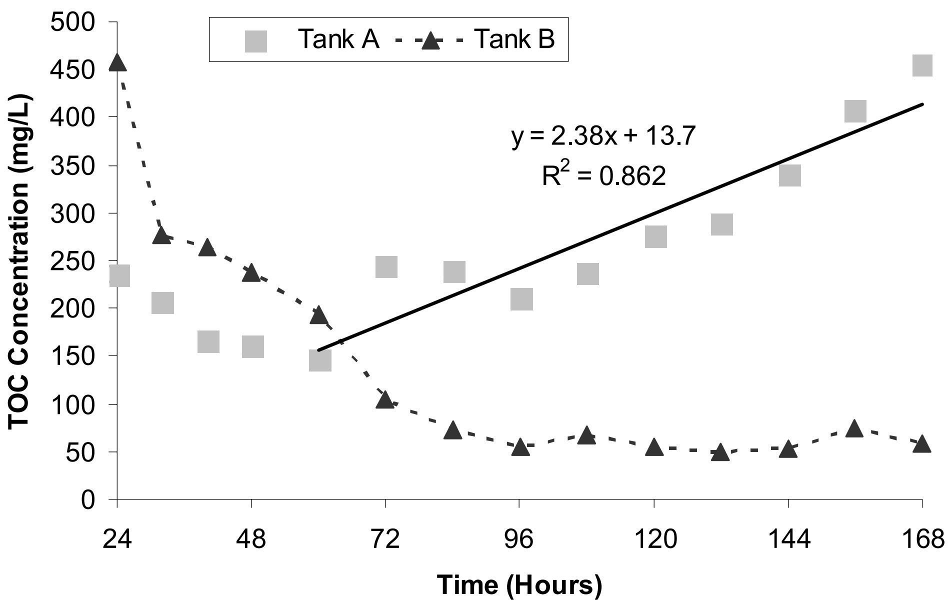

Fig. 8. Total organic carbon (TOC) concentrations observed during days 2-7 (tanks A and B).

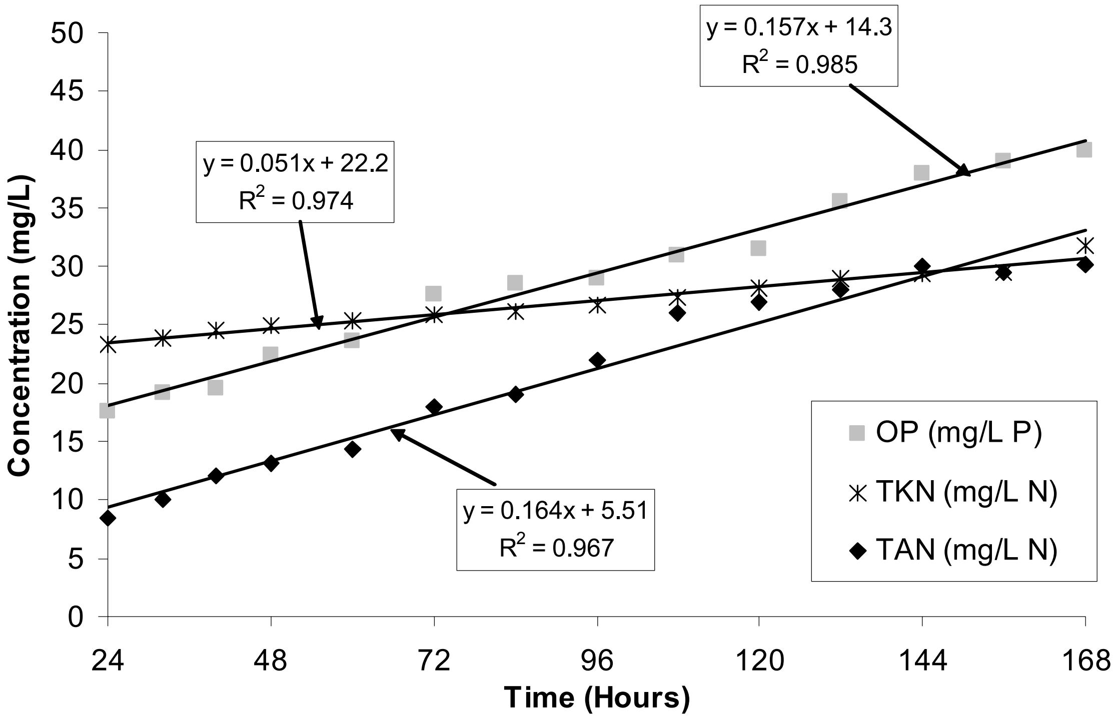

Fig. 9. Tank A linear regressions for ortho-phosphate (OP), total Kjeldahl nitrogen (TKN), and total ammonia nitrogen (TAN) concentration increases during days 2-7.

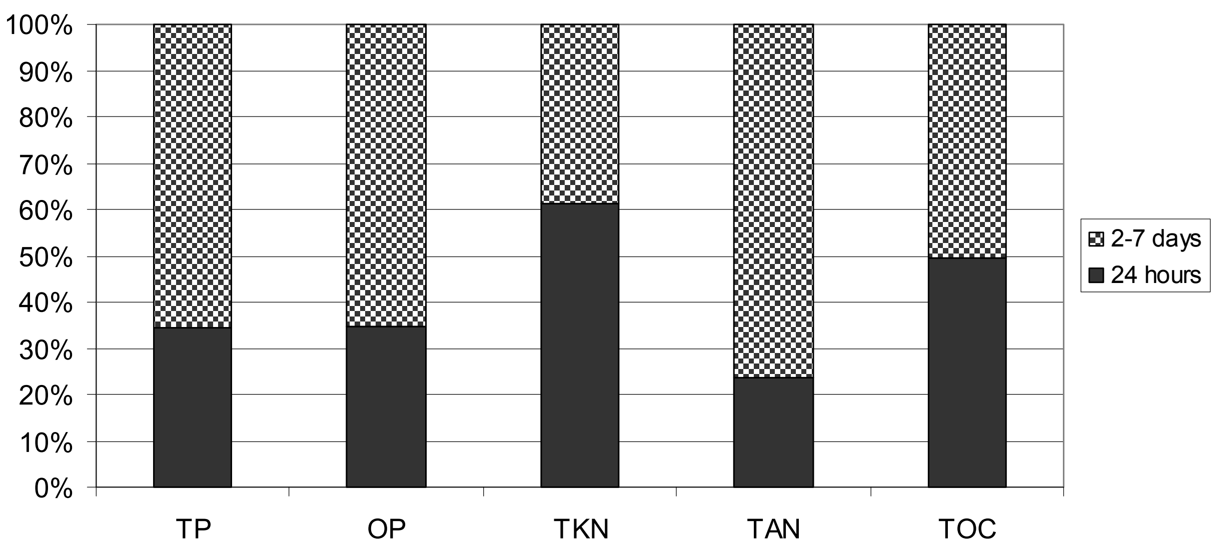

Fig. 10. Percent of total leaching occurring during first 24 hours versus 2-7 day period in tank A.

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Vita:

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