SLOW SAND FILTRATION TECHNOLOGIES FOR THE CONTAINMENT OF NON-INDIGENOUS SPECIES IN RECIRCULATING AQUACULTURE EFFLUENTS

D. G. Drennan II, M. M. Rahman, R. F. Malone

ABSTRACT

With the increased focus on the use of recirculating aquaculture systems for intensive fish culture, the development of options for the management and treatment of system effluents is considered a high priority. Slow sand filter technologies were investigated for the treatment of aquaculture effluents, particularly for the containment of non-indigenous aquaculture species. Slow sand filters have the distinct advantage of being economical to construct and simple to operate, in addition to being extremely efficient in the removal of suspended solids, while providing reliable biofiltration. The authors investigated the feasibility of using a slow sand filter for the containment of tilapia eggs and/or fry in recirculating system effluents. The slow sand filter investigated had a surface area of 1.2 m². Clogging of the bed occurred on an average of every 5 days due to high solids loading (g TSS/m²-day) when operated intermittently and within the recommended hydraulic loading rate (m³/m²-day). While complete containment of tilapia eggs and/or fry was achieved and improvements in water quality observed, the authors feel certain modifications to the design offered here are warranted.

Keywords: slow sand filtration, aquaculture, recirculation, effluents, non-indigenous species

INTRODUCTION

Slow sand filtration is one of the most ancient water treatment techniques (Huisman and Wood, 1974). Although considered by many to be out-dated and old-fashioned, the authors feel it has some unique advantages for the treatment of aquaculture effluents. In fact, slow sand filtration is the only treatment method where purification is achieved through mechanical straining, sedimentation, inertial and centrifugal forces, diffusion, mass-attraction, and electrostatic attraction, as well as biochemical and microbial actions (Graham, 1988). The authors feel that slow sand filtration under certain circumstances is not only the cheapest and simplest, but also the most efficient method of removing particulate material from aquaculture effluents.

In the United States, recirculating technologies are increasingly being adopted to enhance production of highly valued aquaculture products including alligators, soft-crabs and crawfish, tropical and ornamental goldfish as well as tilapia, hybrid stripped bass and sturgeon, just to name a few. The advantages recognized as characteristic of recirculating aquaculture systems are well documented (Van

1 D. G. Drennan II, Research Associate, R. F. Malone, Associate Professor, M. M. Rahman, Graduate Research Assistant, Louisiana State University, Department of Civil Engineering, Baton Rouge, LA 70803-6405.
Gorder, 1991). A properly designed system can be placed almost anywhere and used to produce a high quality product continuously throughout the year.

Increasingly, concerns have been raised regarding the environmental impacts of intensive culture of aquatic organisms (Liao and Mayo, 1974; Mudrak, 1981; Brune, 1991; Iwama, 1991). The benefits of using water recirculation systems to mitigate the impact of intensive aquaculture effluents have been documented (Liao and Mayo, 1974; Iwama, 1991). Recirculating systems moderate the impact of many dilute aquacultural waste discharges, but generate a concentrated sludge stream that must be treated, according to environmental regulations (EPA, 1992), prior to discharge into the environment.

Sludge in recirculating aquaculture systems originates from the feed. Assuming a feed conversion ratio of 1 to 2, and neglecting the impact of uneaten food, 80% of the feed (on a dry mass basis) put into the system will eventually be wasted as fish excretion products (Hopkins and Manci, 1989). The sludge volume generated from a recirculating system is controlled by the amount of solids produced (measured as kilograms of dry weight solids) and the degree to which the solids are concentrated in the effluent stream (Malone, 1992). Sludge concentration is controlled by the solids removal technique employed. Total sludge production from a recirculating system can be estimated by considering direct fish excretion, solids breakdown, and biofloc production during biofiltration through a mass balance analysis which considers the major solids fluxes (Malone, 1992). Sludge produced by a recirculating system is composed of biodegradable organic solids, non-biodegradable organic solids and inert, non-organic material (Benfield and Randall, 1978; Chudoba and Tucek, 1985; Krishnamoorthy and Loehr, 1989). The sludge is characterized as being partially stabilized by the bacterial activity of the system with solids content (TSS) generally being less than one percent on a volumetric basis.

Strategies must also be developed for reducing the risks from the introduction of non-native aquatic species from aquaculture systems (Shelton, 1986). While the use of exotic organisms offers considerable potential for aquaculture in the U.S., adequate safeguards to prevent escape and naturalization should be present (Shelton, 1986). Considerations should be made when designing and building a recirculating aquaculture system to prevent the release of non-indigenous species (eggs and/or fry) to the environment through system effluents. Regulations regarding the culture of non-native species vary from state to state and depend largely on the species being cultured. With the ability of recirculating systems to be located virtually anywhere and to culture a huge diversity of species, containment of eggs and/or fry is a potential problem with national ramifications.

Tilapia are an excellent example of a non-native fish whose popularity as an aquaculture species has grown tremendously in the last few years. In fact, according to the American Tilapia Association, tilapia are grown in almost every state in the nation. Introduced into North America in the early 1950’s (Iversen, 1976), tilapia culture began some 4000 years ago, even before that of carp (Balarin and Hatton, 1979). Two potential problems identified early in the history of tilapia culture are the prolific, precocious breeding, which, if left unhindered, can lead to overcrowding and stunted growth (Balarin and Haller, 1982) and the inability of tilapia to survive water temperatures below 10°C for more than a few days (Chervinski, 1982).

Tilapia’s lack of cold tolerance initially lead to the use of heated over-wintering units (Avalt et al., 1968), but has evolved to the use of intensive, indoor, recirculating production systems. These systems utilizing geothermal resources, waste heat from industry or any number of energy sources have lead to the culture of tilapia in almost every state and thus the potential for the introduction of tilapia into the natural waters of the United States. While not originally considered a problem in the northern states, isolated cases where tilapia have over-wintered in warmwater effluents have lead to
strict regulations even in states such as Pennsylvania (Van Gorder, 1993) where water temperatures routinely drop below 10° C. This has led other states, especially those with milder climates, to implement even stricter regulations regarding the culture of tilapia. In Louisiana, for example, tilapia culture is limited to indoor, recirculating systems only, where the operator must account of 100% of the waters leaving the system to ensure that no eggs and/or fry are released into the wild.

**Slow Sand Filtration**

Slow sand filters have a proven track record and are still the method of choice for water purification in several highly industrialized cities as well as many rural areas (Huisman and Wood, 1974). Slow sand filters have the distinct advantage of being economical to construct and simple to operate. In addition to being extremely efficient in the removal of suspended solids, and reduction of biochemical oxygen demand (BOD), they also provide reliable nitrification (EPA, 1992). Denitrification has also been shown to occur in slow sand filters, with the removal of applied nitrogen being as high as 50% (Burden, 1988; EPA, 1992). Phosphorus removal through adsorption by the filter media is typically observed at initial filter start-up, but declines thereafter as saturation of the media is reached (EPA, 1992).

The filter bed consists of relatively small sand with an effective grain size fine enough to prevent penetration of clogging material without being so fine as to cause an increase in headloss through the filter. The under-drainage system, although unseen, provides unobstructed passage of the treated waters through the filter. It is constructed of several layers of gravel of diminishing size such that the bottom layer of the gravel has an effective diameter of at least twice the size of the slots or holes in the under-drainage support.

During normal operation, effluent waters are introduced onto the filter bed where they slowly pass downward through the interstices between the sand grains. Most of the suspended particles are retained on the filter bed. As a result, a thin, slimy matting of mostly organic material called a "schmutzdecke" forms on top of the bed (Huisman and Wood, 1974). Microorganisms abound in this layer where they consume the organic materials.

Having passed through the schmutzdecke, the water then enters the filter bed. During passage through the bed the fine colloidal particles and bacteria which failed to be retained on the bed are brought in contact with the surface of the sand grains. Due to mass attraction and/or electrostatic forces, these particles become attached to the sand grains (Graham, 1988). In the presence of oxygen, the filter bed also operates as a "fixed film" biological reactor. Heterotrophic and chemotrophic bacteria become evenly coated on the sand grains. The heterotrophs obtain their energy from the organic compounds (uneaten food and excreted waste) and convert them to simple inorganic compounds while the chemoautotrophs obtain their energy by converting the inorganics. The bacteria living in the thin film draw dissolved wastes, oxygen, and other required nutrients from the passing water (Wheaton, 1977; Spotte, 1979). As a consequence, the quality of the recirculating system effluent which entered the bed laden with a variety of suspended solids, dissolved organics, and bacteria, has, in its passage through the filter bed, been improved drastically.

**OBJECTIVES**

The underlying objective was to determine the feasibility of using slow sand filtration for the containment of eggs and/or fry in recirculating aquaculture system effluents. Slow sand filtration was investigated as a method to facilitate the capture of tilapia eggs, larvae, and/or fry from the effluent.
waters of a recirculating system. A determination of the impact of slow sand filters on certain water quality parameters within recirculating aquaculture system effluents was also investigated.

MATERIALS AND METHODS

Recirculating System

The recirculating system which provided the bulk of the waste loading to the slow sand filter consisted of a 10,675 L circular fiberglass fish culture tank with a flat bottom, a 3/4 hp centrifugal water pump for circulation and a bubble washed bead filter (Arman Aquaculture’s Model BBF-3) for both biofiltration and solids capture. A regenerative blower provided aeration to the system and prevented in-tank settling. Water was pumped from the bottom of the culture tank through a perforated manifold extending outward from the side of the tank to the center. A flow rate through the filter of 113 L/min ensured a complete system turnover every 94 minutes. This system contained 61.75 kg of hybrid tilapia (Tilapia mossambica x Tilapia aurea). The feed rate was fixed at 1.1 kg of feed (35% protein) per day. The filter was acclimated prior to introduction of the tilapia, and data collection began 30 days after the fish were introduced into the system.

A small tilapia hatchery system consisting of eight 134 L rectangular tanks, a common sump, a 3/4 hp centrifugal water pump for circulation and a bubble washed bead filter (Arman Aquaculture’s Model BBF-1.5) also utilized the slow sand filter. This system contained approximately 4.2 kg of tilapia brood fish, feed less than 1% body weight per day. Due to the light fish/food loading on the BBF-1.5, the organic loading was considered negligible from this system. Thus, this system only served to increase the hydraulic loading on the slow sand filter.

The bubble washed bead filters employed in this project provided for solids removal, BOD₅ reduction, and nitrification. Low density polyethylene beads, 3-5 mm in diameter, with a specific surface area of 1046.6 m²/m³ (Wimberly, 1990; Chitta, 1993) were employed as a filter media in an upflow pressurized filter configuration. The beads are less dense than water, float above an injection line, and are retained in the filter by a slotted pipe. The BBF-3 contains 0.085 m³ of low-density polyethylene beads, while the BBF-1.5 contained only 0.042 m³. The significance of this filtration approach is that it not only combines biofiltration and solids capture in a single unit but also affords extremely low water loss associated with solids removal, while providing a high specific surface area for biofiltration.

The bead filter was specifically designed to facilitate the rapid growth of both nitrifying and heterotrophic bacteria. During a typical filter cycle, heterotrophic bacteria rapidly grow in the pore spaces between the beads, extracting dissolved organics (BOD) from the circulating waters. Slower growing nitrifiers coat each bead, providing for conversion of the toxic ammonia and nitrite to the stable nitrification end product, nitrate (Colt and Armstrong, 1981). As solids and bacterial biomass accumulate, the bead bed begins to clog, impeding the transfer of oxygen and nutrients to the bacteria in the filter. Washing is accomplished by draining the water from the filter. As the water level drops, the beads and water are forced through the washing neck of the filter where a combination of water and bubbles scrub the beads just before they fall into an expansion chamber. The beads are retained in the filter via a slotted pipe. Following flushing (the BBF-3 loses 151.4 L of water and the BBF-1.5 losses 75.7 L of water), the sludge valve is closed, the pump is switched back on and the beads float upwards, reforming the packed bed. The slow-growing nitrifying bacteria benefit from their attachment to the beads and are retained in the bed.
Slow Sand Filter

The slow sand filter employed in this study had a surface area of 1.2 m² and a filter bed depth of 30.48 cm. The tank was constructed of fiberglass and built with inset ledges to facilitate installation of the under-drainage system. A sloped bottom and sump were also incorporated into the design to facilitate complete drainage (Fig. 1). The under-drainage system consisted of a metal grate to support the weight of the entire filter bed. A sheet of plastic louvering (12.7 mm x 12.7 mm mesh) was then employed to evenly distribute the weight of the filter bed and support the 3 mm square plastic mesh netting. The netting was used to contain the bottom layer of gravel and was an integral part of the under-drainage system. Several layers of gravel and sand of diminishing size were placed immediately on top of the 3 mm square plastic netting such that the bottom layer of gravel had an effective size twice the size of the holes in the under-drain system. Graded filter media was utilized (gradations based on U.S. Standard Sieve Sizes). The bottom layer of the filter bed consisted of 7.62 cm of 6.35-3.17 mm gravel. Next was a 3.81 cm layer of 3.36-2.00 mm sand, then 3.81 cm of 2.38-1.19 mm sand, followed by 15.24 cm of .84-.42 mm sand. To prevent erosion, a second sheet of 3 mm square plastic netting was place over the top layer of sand and the water was introduced to the full length of the bed through a perforated manifold.

The filter was operated as an intermittent slow sand filter. The filter bed was flooded once daily with the recirculating system effluent and permitted to drain between applications. Recommended hydraulic loading rates for slow sand filters range from 0.03 to 0.4 m³/m²-day (EPA, 1992). Once the hydraulic loading rate is exceeded, ponding of the filter surface occurs, indicating the need to clean the bed. The filter bed is cleaned by allowing it to completely dry and then scrapping the schmutzdecke off the top layer of sand. After several cleanings, the addition of new sand was required to maintain a constant bed depth. Complete drying of the bed before cleaning greatly facilitated removal of the accumulated solids, as they usually cracked and flaked once dry and were more easily separated from the sand.

Experimental Methods

Effluents from both recirculating systems (approximately 245.7 L) were collected, mixed, and sampled in the system effluent collection/sampling sump before being pumped onto the slow sand filter bed through the distribution manifold (Fig. 2). The slow sand filter effluent was then collected, mixed, and sampled in the slow sand filter effluent collection/sampling sump before being discharged from the building. Both filters were flushed onto the slow sand filter daily; although, samples were collected weekly. Water quality parameters and analysis procedures are given in Table 1.

RESULTS

Water Quality

As seen in the Table 2, the total ammonia nitrogen (TAN) and nitrite were reduced by 16.59% and 56.69% respectively across the filter bed. The reduction in TAN and nitrite indicates the filter bed was operating under aerobic conditions and that a substantial population of nitrifying bacteria (Nitrosomonas sp. and Nitrobacter sp.) was present within the schmutzdecke and/or the bed itself.

Total suspended solids (TSS) and volatile suspended solids both showed the greatest percent removal through the bed, 93.12% and 93.71%, respectively. The high effluent TSS value (35.69 mg/L) may be attributed to the biofloc growing in and on the tank walls beneath the filter bed, feeding on the nutrient rich waters.
Figure 1. Sectional View of the Slow Sand Filter

Figure 2. Experimental Apparatus Used in Conducting Slow Sand Filter Evaluation
Table 1. Water Quality Parameters and Analysis Procedures\(^a\) used in Evaluation of the Slow Sand Filter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analysis Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Ammonia Nitrogen</td>
<td>Distillation and Nesslerization - colorimetric</td>
</tr>
<tr>
<td>Nitrite</td>
<td>Diazotization Method - colorimetric</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand</td>
<td>Winkler with Azide modification/thiosulfate titration</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>Vacuum filtration/drying over 103 - 105(^\circ) C</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>Filtration/Evaporation 108(^\circ) C to dryness</td>
</tr>
<tr>
<td>Volatile Suspended Solids</td>
<td>Vacuum filtration/muffle furnace 550(^\circ) C</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Turner Designs Nephelometer</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>Digestion and Ascorbic Acid</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Mullin and Riley Reduction Method</td>
</tr>
</tbody>
</table>

\(^a\)All procedures from Standard Methods (APHA, 1989)

Table 2. Water Quality Analysis Results for the Slow Sand Filter Mean (STD deviation) and Range.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n</th>
<th>Influent</th>
<th>Effluent</th>
<th>Percent Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Ammonia Nitrogen</td>
<td>6</td>
<td>1.16 (0.88)</td>
<td>0.96 (0.59)</td>
<td>16.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.31 - 2.97</td>
<td>0.15 - 2.10</td>
<td></td>
</tr>
<tr>
<td>Nitrite</td>
<td>9</td>
<td>0.74 (0.48)</td>
<td>0.32 (0.37)</td>
<td>56.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30 - 1.78</td>
<td>0.02 - 1.03</td>
<td></td>
</tr>
<tr>
<td>Biochemical Oxygen Demand</td>
<td>7</td>
<td>25.29 (6.97)</td>
<td>14.73 (9.79)</td>
<td>41.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13.62 - 37.00</td>
<td>6.00 - 36.00</td>
<td></td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>6</td>
<td>518.79 (131.40)</td>
<td>35.69 (16.22)</td>
<td>93.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>327.00 - 708.00</td>
<td>14.00 - 68.00</td>
<td></td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>8</td>
<td>1085.25 (261.72)</td>
<td>1061.88 (299.51)</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>717.00 - 1632.00</td>
<td>642.00 - 1577.00</td>
<td></td>
</tr>
<tr>
<td>Volatile Suspended Solids</td>
<td>7</td>
<td>444.11 (121.74)</td>
<td>27.93 (13.45)</td>
<td>93.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>276.00 - 640.00</td>
<td>10.00 - 55.00</td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>6</td>
<td>24.18 (4.87)</td>
<td>10.32 (6.90)</td>
<td>57.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.20 - 31.20</td>
<td>2.70 - 24.00</td>
<td></td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>6</td>
<td>13.60 (2.36)</td>
<td>13.28 (2.65)</td>
<td>2.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.00 - 16.73</td>
<td>9.56 - 16.58</td>
<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td>6</td>
<td>16.10 (2.75)</td>
<td>16.26 (3.61)</td>
<td>-0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.58 - 20.24</td>
<td>10.26 - 22.70</td>
<td></td>
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</tbody>
</table>
Volatile suspended solids (VSS) is the organic component of TSS. The VSS fraction of TSS in wastewater systems typically ranges from 0.7 to 0.8 (Metcalf and Eddy, 1979), although higher values are usually found in aquaculture systems due to the large amount of biomass discharged as sludge (Coffin, 1993). The values we observed are what would be expected from a recirculating system, 0.9 for the slow sand influent and 0.8 for the effluent. Along these same lines, as the TSS decreased, we would also expect a similar decrease in VSS across the filter bed, which in fact is exactly what we observed, resulting in a almost identical percent removal for the TSS and VSS.

Biochemical oxygen demand is expressed in both soluble and particulate forms. Based on a study of channel catfish (Ictalurus punctatus), Murphy and Lipper (1970) reported the soluble BOD<sub>5</sub> as 58% of the total BOD<sub>5</sub> excreted; whereas, BOD<sub>5</sub> in particulate matter was 42%. Wimberly (1990), however, found that only 23% was expressed in the soluble form and 77% was in the particulate form. Correspondingly, the authors observed a 41.75% reduction in BOD<sub>5</sub> with a 93.12% reduction in TSS which indicates 44.83% of the BOD<sub>5</sub> was in the particulate form.

Although turbidity removal across the filter bed was 57.34%, effluent turbidities were still considered high (10.32 NTU). The high effluent turbidity can be associated with the remaining TSS in the slow sand filter effluent (35.69 mg/L).

There was very little change in the total phosphorus across the filter bed, only 2.5%. There was no reduction in nitrate levels across the bed, which is to be expected since the bed was operating aerobically.

**DISCUSSION**

The maximum particle size a sand filter will pass is determined by the sand grain size. larger sand grains allow larger particles to pass (Wheaton, 1977). The sand size chosen for the top layer of the filter bed was 0.84 to 0.42 mm in diameter, thus it was designed to trap particles larger than the smallest grain size present (0.42 mm). Tilapia egg size tends to be species specific (Lowe, 1955b); although, Hanson (1975) gives a range of egg sizes from 1.6 to 3.5 mm in diameter for eight different species of tilapia. Just after hatching, the same eight different species of tilapia fry range in length from 3.5 to 6.8 mm (Hanson, 1975).

The slow sand filter investigated here provided complete protection from the release of tilapia eggs and/or fry. On numerous occasions, tilapia fry were observed in the system effluent collection/sampling sump; however, fry were never observed in the sand filter effluent collection/sampling sump. Thus, the authors feel that slow sand filtration is more than adequate for the containment of this non-indigenous species within recirculating aquaculture system effluents. However, due to the high solids content of recirculating system effluents, estimated to be in the range of 0.05% to 0.50% for bead filters (Chen et al., 1992), frequent clogging of the bed was observed, requiring frequent cleaning.

Hydraulic loading on the filter under investigation was estimated to be 0.20 m<sup>3</sup>/m<sup>2</sup>-day, well within the recommended range. However, pooling occurred on average every 5 days, requiring filter cleaning. The authors believe this is related to the high particulate content of the system effluent. Solids loading on the slow sand filter was estimated to be 98.17 g TSS/m<sup>2</sup>-day (on a dry weight basis). However, data on organic loading rates are not widely available since slow sand filter designs are generally based on hydraulic loading rates.
Although the slow sand filter performed flawlessly with respect to the containment of non-indigenous species within aquaculture effluents and provided reasonable improvements to the quality of the effluents, the authors feel that modifications to the design and operation are necessary to increase the time interval between cleaning, reduce the overall operating and maintenance costs, and further improve the water quality of the slow filter effluent.

The authors propose to use a simple settling basin to remove the particulate matter from the system effluent before it is introduced onto the slow sand filter. Liao and Mayo (1974) found that a settling basin with a retention time greater than 15 minutes was sufficient for removing most settleable solids. Harman (1978) also claimed that a well designed settling basin can remove the majority of settleable solids which he estimates to constitute 60% to 70% of the TSS.

Assuming 70% of the solids settle out, the solids loading on the filter will decrease to 29.45 g TSS/m²-day. Consequently, the time interval between cleaning will increase from 5 days to 15 days. The bed will be cleaned as before, while the small amount of accumulated sludge in the clarification basin must be treated prior to discharge to ensure no eggs and/or fry are present. This can be accomplished chemically (chlorox) before discharge or by applying the concentrated sludge to some sort of sludge drying bed (EPA, 1992) and later applying it to the land as soil conditioner/fertilizer (Olson, 1991).

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