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Reducing phosphorus discharge from flow-through aquaculture III: assessing high-rate filtration media for effluent solids and phosphorus removal

Brit True, William Johnson, Shulin Chen*

Biological Systems Engineering, Washington State University, PO Box 646120, Pullman, WA 99164, USA

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Abstract

Two types of unique high-rate filtration media, reticulate foam media of four porosities and Fuzzy filter® (FF) media (Schreiber Technologies, Trussville, AL, USA), were tested during bench top and field tests for potential application in flow-through (FT) mechanical filtration processes to reduce solid phase phosphorus (P) discharge. Bench top test screening was used to select medias for field testing based on the following criteria: (1) capable of particle size capture down to 100 μm; (2) capable of hydraulic loading $\geq$2037 Lpm/m^2 [50 gpm/ft^2]; (3) initial clean bed head loss $\leq$ $\sim$152 mm. Bench top results showed average particle size capture of 217, 161, 118, 69, and 51 μm for the four porosities of reticulated foam tested and the FF media, respectively. Fuzzy filter® media was the only media that was unable to sustain the 2037 Lpm/m^2 hydraulic loading; therefore FF media was tested at a hydraulic loading of 1605 Lpm/m^2. The FF media was also the only media that which exhibited any measurable head loss during the 1 h bench top tests, i.e. 17 cm water. Based on these results the 30 ppi reticulated foam was selected for a 16 h field test to measure particle size capture, head loss, and the effect on solids and P discharge from commercial FT raceway effluent. The results indicated particle size capture of less than 100 μm, a cumulative head loss of 150 mm, and a 29% reduction in suspended solids and solid phase phosphorus discharge (11% total phosphorus discharge reduction) from the filtered effluent. The results support that the 30 ppi reticulated foam is a

* Corresponding author. Tel.: +1 509 335 3743; fax: +1 509 335 2722.
E-mail address: chens@wsu.edu (S. Chen).

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suitable media for development in a high-rate filtration process for solids and phosphorus discharge reductions from FT raceway effluent.

Keywords: Aquaculture; Filtration; Phosphorus; Flow-through; Effluent; Treatment

1. Introduction

Flow-through (FT) aquaculture production systems are used worldwide (Pennell et al., 2001) and are the second most prevalent production system used in the USA (USDA, 1998). Phosphorus (P) discharge from FT aquaculture facilities is regulated to mitigate effluent P contributions to receiving waters that may lead to degradation and eutrophication (Rosenthal, 1994; Bergheim and Brinker, 2003; MacMillan et al., 2003). However, the treatment of large FT aquaculture effluent is problematic due to limitations in treatment efficiencies, operational requirements and sizing constraints (True et al., in press).

Cripps (1994) identified two major challenges associated with the treatment of FT effluents, low pollutant concentrations and high flow rates. Cripps compared European FT effluent to domestic wastewater. The comparison showed that total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), and biological oxygen demand (BOD) concentrations were 3% or less than the same components in medium strength domestic wastewater. Flow-through aquaculture also produces more effluent than any other type of aquaculture production system. For a unit production capacity of 1 kg fish per year, FT systems produce 0.16 L/min of effluent (MacMillan, 1992) compared to 0.0034 L/min by pond systems and 0.0002 L/min by recirculation systems (Losordo, 1991; Losordo et al., 1994). Treating this volume of FT effluent with traditional wastewater technologies is often cost prohibitive due to the required size of treatment processes and associated maintenance.

Due to the prevalence of system use, environmental regulations, and the treatment challenge there has been a considerable amount of research on the treatment of FT aquaculture effluents (Cripps and Bergheim, 2000). Common treatments include sedimentation and or mechanical filtration. Mechanical filtration, primarily via micro-screens, is implemented postsedimentation and is an effective treatment for reducing solid phase P discharge from FT aquaculture effluents (Cripps and Bergheim, 2000). However, on large FT facilities, micro-screen filtration effluent treatment is cost prohibitive (Hinshaw and Fornshell, 2002).

Although, the FT facilities in Southern, Idaho, USA have reduced TP discharges by 40% from baseline levels of 1991 (MacMillan et al., 2003) further regulatory mandated reductions are pending. As regulations become more stringent, further P discharge reductions become more difficult and expensive to accomplish. True et al. (in press) concluded that the challenge resided in finding effective and feasible solutions for solids removal if further solid phase P discharge reductions were to be realized.

The purpose of this paper is to identify and characterize mechanical filtration media that could be used in an effective and economic filtration of large FT effluents as described by True et al. (in press) to reduce P discharge.

True et al. (in press) characterized the effluent of two large FT facilities in Southern Idaho, USA. A 40/60% split was found between effluent solid and dissolved phase P, respectively. They also reported that 52% of the discharged mass was greater than 105 μm and that the median volumetrically weighted effluent particle size was 250.1 μm. From that data they estimated a total P discharge reduction of ~20% if solids over 100 μm could be removed from the effluent.

Based on that characterization a set of criteria was established to identify potential filtration media. Suitable media would capture particles ≤ ~100 μm during non-pressurized filtration operation at high hydraulic loads of ≥2037 Lpm/m^2 (50 gpm/ft^2) while exhibiting low head loss (≤ ~152 mm).

Two types of media (Fig. 1) were identified for testing; reticulated foam and a media from a proprietary filter named the Fuzzy filter® (FF) (Schreiber Technologies, Trussville, AL, USA). Poly-urethane reticulated foams are used extensively for many applications including mechanical filtration. The foam's matrix is characterized by an open cell structure, high void volumes (>90%), and compressibility making it ideal for filtration applications. For water filtration applications, poly-urethane and poly-ether foams are the most suitable due to their inert nature in water. Although many of the foam's material and air filtration properties are well characterized by manufacturers, data concerning the water filtration properties is limited.

The Fuzzy filter® is a pressurized, high-rate, compressible bed filter for wastewater applications. The media is a collection of polyvaniladene synthetic fibers bound into discrete porous, compressible, balls of ~3 cm in diameter. The FF was tested on secondary clarifier effluent from a complete-mix, activated-sludge process wastewater treatment facility by Caliskaner et al. (1999). They found that the TSS and turbidity removal of the FF was similar to other conventional filters. However, the filtration rate was three to six times greater with significantly less backwash water required.

Although reticulated foam and FF media have been characterized for other filtration applications, no work has been done to examine their properties for solids filtration on aquaculture effluents including FT aquaculture effluents. The purpose of this study was to conduct initial investigations to fill the information gap.

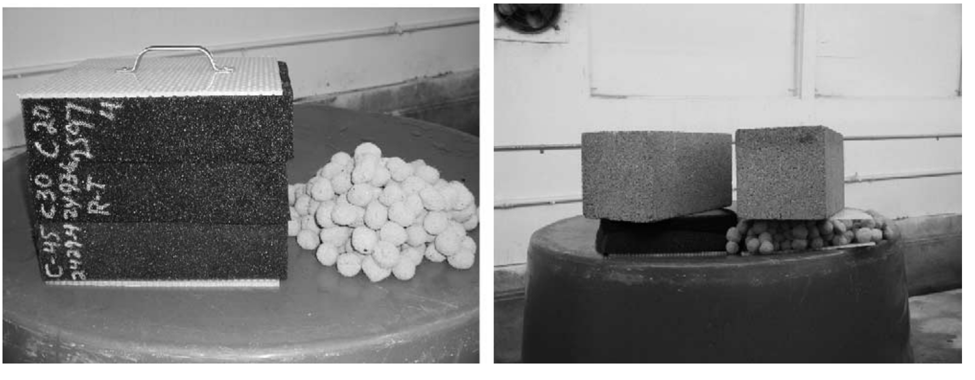

Fig. 1. Reticulated foam (to the left in each picture) and Fuzzy filter® media (to the right in each picture) in the uncompressed and compressed states, left picture and right picture, respectively.

2. Methods

Bench top and field filtration tests with simulated waste and raceway effluent, respectively, were conducted to determine particle size capture capabilities and head loss behavior of the reticulated foam media of four porosities; 10, 20, 30 and 45 pores per inch (ppi) and the FF media.

2.1. Bench top testing

The reticulated foam was obtained courtesy of Foamex (Eddystone, PA, USA) and Crestfoam (Moonachie, NJ, USA). Schreiber Technologies, the licensed proprietor and developer of the Fuzzy filter supplied the FF media®. Acrylic test reactors were used in bench top and field tests. The reactors measured ~10 cm i.d. × 50.8 cm long, and held a 40 cm bed depth of test media.

The reticulated foam test beds were composed of four ~10 cm diameter × 10 cm height foam cylinders one on top of the other, while the FF media was placed in the column and compressed ~15% to fill the 40 cm bed depth. The media was supported between perforated polyethylene plates positioned at the top and bottom of the test reactor. An additional plate that was 5 cm above the top of the media was used to distribute influent across the media surface.

Tests were conducted for 60 min with simulated FT effluent. The simulated effluent was composed of crushed sinking trout feed (4 mm, pelleted feed, Clearsprings Foods Inc.), sieved to approximate the particle size distributions in measured FT facility effluent (True et al., in press). The average median volumetrically weighted particle size of the simulated waste was within 3% of the value for median FT effluent particle at FT facilities in Southern Idaho, USA. The crushed, sieved feed was mixed immediately prior to use in 946 L (250 gal) tanks, at a total suspended solids concentration of 10 mg/L, which was necessary to meet particle size analysis limits.

The simulated effluent was kept under vigorous aeration before being pumped to the test reactor with a 70 W submersible centrifugal pump. The pump had negligible effects on the particle size distributions as confirmed by test samples, analyzed for particle size distribution, taken before and after passing through the pump. During bench top tests the upper range of hydraulic loading rates was selected as a screening parameter to challenge the media. The reticulated foams were tested at 4432 ± 336 Lpm/m^2 (109 ± 8 gpm/ft^2); however the FF media was unable to sustain such loads and was tested at 1605 ± 110 Lpm/m^2 (39 ± 3 gpm/ft^2).

Three paired 500 mL influent and effluent samples were collected at 5, 30, and 60 min during the test. Samples were analyzed in triplicate within 24 h for particle size distribution using the Mastersizer S laser diffraction particle size analyzer (Malvern Instruments, Worcestershire, UK). Results were recorded as volumetrically weighted particle sizes at a measured percentage within the sample. Head loss for each media was also visually recorded at 5, 30, and 60 min during the tests. Based on the screening parameters tested, medias were selected for field testing if the (1) particle size capture was ~100 μm and (2) at a hydraulic loading rate ≥2037 Lpm/m^2 (50 gpm/ft^2) with a head loss ≤ ~152 mm (6 in.) at the test's conclusion.

2.2. Field testing

The field tests were conducted at a large FT raceway facility in Southern Idaho, USA (Farm 2 as described by True et al., in press). The raceway which provided the test effluent was stocked with rainbow trout of ~35 cm long at a density of 27 kg/m^3. The effluent was characterized by a TSS concentration greater than 10 μm of 1.35 mg/L and a total P discharge of 0.09 mg/L; 35% of which was attributed to the solid phase and the remaining 65% to the dissolved phase. Thirty pores per inch reticulated foam was used in the field test in the same configuration described in the bench top tests. The filter reactor was fed with last use raceway water that was gravity fed via a 5 cm diameter flexible PVC pipe. The piping was positioned to siphon raceway effluent postquiescent zone settlement and at half of the raceway water depth. The flow rate was controlled by a ball valve to 3,049 Lpm/m^2 (75 gpm/ft^2) and measured during testing via four calibrated volume and time measurements at 0, 5.3, 10.6, and 16 h. Particle size distribution samples as well as head loss measurements were also taken at the same measurement times.

In order to obtain detectable amounts of suspended solids, 75 L of test filter influent was concentrated over a 10 μm filter bag. The collected material was rinsed into 1 L sample bottles for PSD analysis, which was conducted within 24 h at Washington State University in the same manner as described for bench top tests. Total suspended solids were analyzed according to Standard Methods procedure 2540D. These same procedures were also used for analyzing the filter effluent samples. The head loss was measured visually at each sample period. At the conclusion of the test each of the four foam cylinders composing the filtration bed were rinsed with 15 L of distilled water. A 1 L sample of rinse water was taken from each rinse and analyzed for TSS and PSD. This data was utilized to determine the effect on solids and P discharge due to reticulated foam filtration treatments.

3. Results and discussion

3.1. Bench top testing

Table 1 provides the average experimental hydraulic loading rates, the cumulative head loss, and average influent and effluent particle size capture for each media type. The predetermined hydraulic loading rate was selected as 4432 ± 336 Lpm/m^2 (100 ± 8 gpm/ft^2) and all reticulated foams were tested at this level and exhibited no measurable head loss during the 1 h test duration. The FF media was the only media that could not be tested at 4432 Lpm/m^2, as well as the only media to exhibit head loss during the test. The FF media was tested at 1605 ± 110 Lpm/m^2 (40 ± 2.7 gpm/ft^2) with a final head loss of 17.1 cm water at 1 h. Caliskaner et al. (1999) found that clean bed head loss increased linearly as hydraulic loading rate and filter bed compression increased. They also reported initial clean bed head loss of 400 mm of water for a 760 mm bed depth at 15% compression and a hydraulic loading rate of 1230 Lpm/m^2. Initial head loss during this study for a 400 mm bed depth at ~15% compression and 1605 Lpm/m^2 was 64 mm of water. The difference was associated with lower bed compression and the different filter bed depths.

Table 1
Bench top experimental hydraulic loading rates, head loss, and particle size capture measurements

Media		Average hydraulic loading rate (Lpm/m^2)	Final head loss (cm H_2O)	Average influent particle size (μm)	Average effluent particle size (μm)
Reticulated foam (ppi)	10	4432	ND	255.54	216.96
	20	4432	ND	244.43	161.23
	30	4432	ND	210.81	118.33
	45	4432	ND	225.25	69.35
Fuzzy media		1605	17.1	252.41	51.03

ND: non-detected.

Head loss and particle capture measurements for each foam pore size can be seen in Fig. 2. Although all reticulated foams were able to handle the hydraulic loading challenge, the results indicated that particle size capture was clearly dependent on foam pore size, which is a well understood general relationship for mechanical filtration. Average cell diameters for Foamex reticulated foams are shown in Fig. 3. Experimental particle size capture was seen to vary with average cell diameters, but was not directly correlated indicating interception as the likely predominant removal mechanism. The average particle size captured by the 10 and 20 ppi foams was 217 and 161 μm, respectively. The 10 ppi had little effect on the influent particle size distribution; however the 20 ppi initially captured

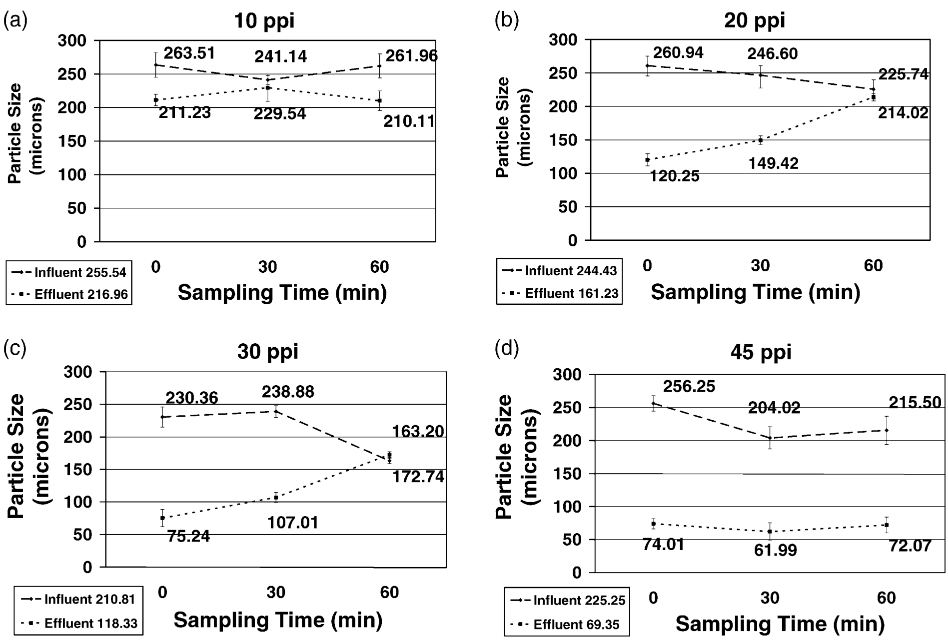

Fig. 2. Bench top influent and effluent particle size for (a) 10 ppi (b) 20 ppi (c) 30 ppi and (d) 45 ppi reticulated foams. Note: Test averages shown in the legend.

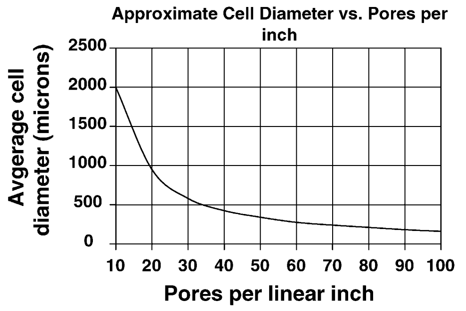

Fig. 3. Average cell diameter as a function of Foamex® reticulated foams. Data taken from Foamex® technical product function sheet.

down to 120 μm, but spiked to an effluent particle size of 214 μm at the conclusion of the test. The 30 and 45 ppi foams both initially captured particles down to 75 and 74 μm, respectively; while the 30 ppi foam effluent particle size spiked to 163 μm and the 45 ppi material maintained particle size capture to 72 μm until the conclusion of the test. The spike in effluent particle size is attributed to the solids break through point; which was qualitatively confirmed by the visible presence of discharged solids in collected filter effluent of the 20 and 30 ppi foams. The presence of particles was not observed in the effluent collected from the 45 ppi foam. The FF media performed best in terms of particle size capture with an average effluent particle size of 51 μm at the ~15% bed compression (Fig. 4).

Although the FF media resulted in the lowest effluent particle size it was deemed not currently applicable for FT effluent treatment under the given criteria. Therefore, the FF media was not selected for further testing due to hydraulic loading constraints and head loss characteristics. Another factor influencing the decision was the fact that simplicity is essential for the success of any proposed mechanical filtration in a large scale FT application. In wastewater applications the Fuzzy media is housed in a pressurized vessel with a mechanism to adjust bed compression and process controlled backwashes to limit head loss. Although such mechanisms simplify filter operation in municipal wastewater applications, many FT aquaculture farms have limited infrastructure and personnel to support such functions.

The 30 ppi reticulated foam was selected for further testing based upon the likelihood that the 30 ppi would provide the best balance between solids capture and minimal head loss under field conditions.

3.2. *Field testing*

The average influent and effluent particle sizes for the field test of the 30 ppi foam were 179 and 92 μm, respectively as shown in Fig. 5. The effluent particle size of the 30 ppi foam remained constant, never exceeding 100 μm. In contrast to bench top tests, there was no apparent solids break through. This is perceived to result from the nature of raceway effluent particles. The organic matter of raceway effluent particles is more viscous and

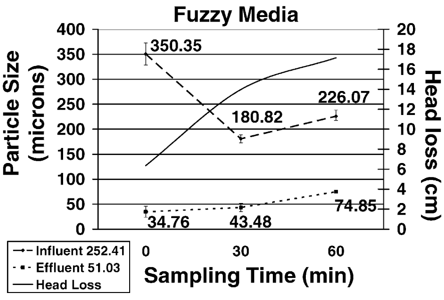

Fig. 4. Bench top influent and effluent particle size for Fuzzy media. Note: Only the Fuzzy media had measurable head loss.

adhesive, which results in a bridging tendency that is more readily intercepted than the discrete sieved particles in the simulated effluent of the bench top tests. The raceway effluent also appears more conducive to being trapped and lodged within the foam's matrix than the simulated feed, which was testified by the lack of a clear solids front break through. As solids were captured the head loss developed linearly to ∼178 mm at the conclusion of the extended field tests (Fig. 5).

Table 2 shows average particle size captured and the total suspended solids (TSS) concentrations in the rinse water from each filter region. From the top (influent) to bottom (effluent) of the test reactor the filter regions were denoted T, MT, MB, and B. Average particle size captured and TSS decreased with increasing filter bed depth. This observation is in congruence with mechanical filtration characteristics. Based on the TSS values and the known volume of rinse water, the solids captured in each section and the cumulative solids capture were calculated (Table 2). Using the filter influent TSS value (1.5 mg/L) and the hydraulic loading rate (3049 Lpm/m^2) the suspended solids removal efficiency and solid phase P discharge reduction were found to be 29%, which, based on the effluent phase distribution, corresponded to an 11% reduction in total P discharge (Table 3).

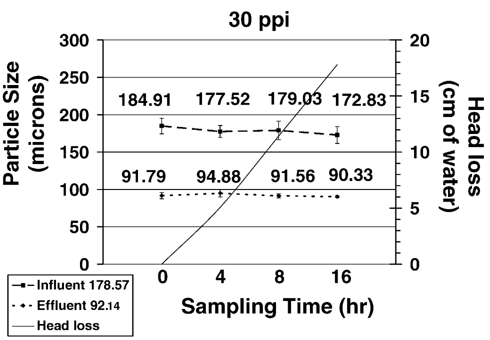

Fig. 5. Particle capture and head loss field test results for 30 ppi reticulated foam filtration trial. Note: Test averages shown in the legend.

Table 2
Field test 30 ppi filter bed particle size and solids capture results

Filter bed section	Median captured particle size (mm)	Rinse water TSS (mg/L)	Filter bed section solids capture (mg)	Total captured solids (mg)
Top	196	407	6105	10185
Middle top	145	127	1905	
Middle bottom	143	68	1020	
Bottom	133	77	1155	

Table 3
A 30 ppi reticulated foam filtration effects on solids and P discharge from raceway effluent

Calculated effect on indicated discharge parameter	Percent reduction (%)
Total suspended solids removal efficiency (10185 mg/34560 mg) × 100	29
Solid phase P dishcharge reduction (10185 mg × 0.02 mg/34560 mg × 0.02 mg) × 100	29
Total P discharge reduction (1 − (0.09 − 0.09 × 0.35 × 0.30)/0.09) × 100	11

4. Conclusions

The 30 ppi reticulated foam media was able to meet each selection criteria and resulted in solid phase and total P reductions during extended field tests. Based on these results the 30 ppi media can be considered as a candidate for use in high-rate mechanical filtration applications for FT systems. Furthermore, this media can be utilized as an integral component in the BMP plan for CAAP facilities under EPA jurisdiction by addressing the general objectives for FT systems such as: manage removed solids and excess feed by minimizing the reintroduction of solids removed through the treatment of the water supply, minimize the discharge of unconsumed food and minimize the discharge of feeds containing high levels of fine particulates or high levels of phosphorus, and maintaining in-system technologies to prevent overflow of any floating matter and subsequent bypass of treatment technologies. Further development of reticulated foam media will involve filter design and the development of an appropriate back wash mechanism.

Acknowledgments

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References

Bergheim, A., Brinker, A., 2003. Effluent treatment for flow through systems and European Environmental Regulations. Aqua. Eng. 27, 61–77.

Caliskaner, O., Tchobanoglous, G., Carolan, A., 1999. High-rate filtration with a synthetic compressible media. Water Environ. Res. 71, 1171–1177.

Cripps, S.J., 1994. Minimising outputs: treatment. J. Appl. Ichthyo. 10 (4), 284–294.

Cripps, S.J., Bergheim, A., 2000. Review: solids management and removal for intensive land-based aquaculture production systems. Aqua. Eng. 22, 33–56.

Hinshaw, J.M., Fornshell, G., 2002. Effluents from raceways. In: Tomasso, J.R. (Ed.), Aquaculture and the Environment in the United States, US Aquacultre Society. A Chapter of the World Aquaculture Society, Baton Rogue, Louisiana, USA, pp. 77–104.

Losordo, T.M. 1991. Engineering considertations in closed recirculation systems. In: Giovannini, P. (Ed.), session chairman, Aquaculture systems engineering, Proceedings of the World Aquaculture Society and the American Society of Agricultural Engineers, 22 June 16–20, San Juan, Puerto Rico. American Society of Agricultural Engineers, Saint Joseph, Michigan, USA.

Losordo, T.M., Westerman, P.W., Liehr, S.K., 1994. Water treatment and wastewater generation in intensive recirculationg fish production systems. Bull. Res. Inst. Aqua. 1 (Suppl.), 27–36.

MacMillan, R., 1992. Economic implications of water quality management for a commercial trout farm. In: Blake, J., Donald, J., Magette, W. (Eds.), National livestock, poultry, and aquaculture waste management. American Society of Agricultural Engineers St. Joseph, Michigan, USA, pp. 185–190.

MacMillan, J.R., Huddleston, T., Woolley, M., Fothergill, K., 2003. Best management practice development to minimize environmental impact from large flow-through trout farms. Aquaculture 226, 91–99.

Pennell, W., Lane, E.D., Dalziel, F., 2001. Open systems the culture of fish for release into natural systems. In: Wedemeyer, G.A. (Ed.), Fish Hatchery Management. 2nd ed. American Fisheries Society, Bethesda, MD, pp. 187–239.

Rosenthal, H., 1994. Fish farm effluents and their control in EC countries: summary of a workshop. Special issue J. Appl. Ichthyol. 10, 215–224.

True, B., Johnson, W., Chen, S., in press. Reducing Phosphorus Discharge from Flow-through Aquaculture I: Facility and Effluent Characterization.

USDA, United States Department of Agriculture, 1998. Census of aquaculture.