Low-Head Saltwater Recirculating Aquaculture Systems Utilized for Juvenile Red Drum Production

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ABSTRACT

The USDA Agricultural Research Service and the Harbor Branch Oceanographic Institute - Florida Atlantic University (HBOI-FAU) Center for Aquaculture and Stock Enhancement are collaborating to evaluate low-head recirculating aquaculture system (RAS) designs for inland low salinity aquaculture production of marine finfish. As part of this project, the systems described were utilized to intensively produce red drum (*Sciaenops ocellatus*) juveniles that would be part of the Florida Fish and Wildlife Conservation Commission's (FWC) Saltwater Hatchery Network Initiative. The design and performance data collected from these systems will be utilized in the engineering and determination of design costs for a statewide public-private saltwater hatchery network. The current low-head RAS design that was evaluated for the Phase I (25 mm to 60 mm standard length, SL) through Phase II (60 mm to > 100 mm SL) production of

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red drum juveniles included a nine-tank system and a ten-tank system. Tank diameters were 1.5 m with a water depth of approximately 1.0 m. Mechanical and biological filtration mechanisms included polygeyser filters, sand filters, moving bed torrus filters, and filter pads. For the Phase II to Phase III (100 to 180 mm SL) production, the red drum juveniles were cultured in four larger-scale replicated RAS low-head systems. Mechanical and biological filtration mechanisms in these systems included moving bed torrus filters, long-flow pathway moving media bed filters, and rotary micron screen drum filters, along with supplemental liquid oxygen addition. The systems presented indicate that intensive inland culture of marine species for commercial aquaculture production or stock enhancement purposes is possible even under the technical constraints of low-head system operation.

INTRODUCTION

The red drum, *Sciaenops ocellatus*, (also known as redfish) is an important commercial and recreational fish species in the Gulf of Mexico and the Atlantic Ocean (Sandifer *et al*. 1993). This species is highly valued by both fishermen and consumers. In Florida, sport fishing is a significant tourist activity with a total of 885,000 anglers coming to the state, ranking Florida the number one freshwater and marine fishing destination in the United States (ASA 2006). Its expanded popularity has decreased wild stocks and resulted in restrictions on commercial harvests. During the late 1980s, red drum populations were declining drastically. This decline was halted by eliminating commercial harvesting and applying very restrictive regulations on the recreational harvest (Murphy 2006, FWC 2008). Despite these fishery restrictions, red drum stocks have not recovered to the point where harvest restrictions can be relaxed, an expressed desire of many red drum anglers. Consequently, red drum has become an important species for commercial aquaculture production and for cultivation by state agencies for stock enhancement efforts. To address concerns related to overexploited natural stocks, the Florida Fish and Wildlife Commission (FWC) is working with partners in the public and private sector to develop an expanded ability to produce saltwater fish for stocking. Florida's marine fishery resources, based on direct recreational fishery expenditures and wholesale value received by the commercial fishery, are valued at close to two billion dollars annually. This resource translates to as much as eight billion dollars annually through industry related jobs (Babieri 2008). Because of the strong recreational fisheries interest, the Florida FWC is expected to protect and enhance the marine fishery resources for Florida's residents, tourists, and future generations.

Expansion of Florida's marine hatchery production will assist conservation and restoration of declining fisheries and stimulate economic growth. FWC has operated a marine hatchery at Port Manatee, FL since 1988. During this time the FWC has raised and released millions of fish, with more than 4 million red drum released statewide. The vision for the FWC Saltwater Hatchery Program is to have a network of marine hatcheries directed towards development of reliable hatchery technology for mass multi-species production of fingerlings using recirculating aquaculture technology, and to integrate fish stocking efforts with habitat enhancement.

As part of this vision, the Center for Aquaculture and Stock Enhancement at Harbor Branch Oceanographic Institute - Florida Atlantic University (HBOI-FAU), in cooperation with the Engineering Unit of the Sustainable Marine Aquaculture Systems project of the USDA Agricultural Research Service, are collaborating with Florida FWC to develop indoor fingerling grow-out systems to intensively produce red drum juveniles. The design and performance data collected from these systems will be utilized to design the recirculating aquaculture systems that FWC plans in the new hatcheries/ecocenters throughout the state of Florida. Establishment and testing of recirculating aquaculture technologies using resources under specific climatic and culture conditions is a significant approach for maximizing water reuse and enhancing marine fingerling production for stock enhancement throughout the state of Florida. The design of the Phase I (25 mm to 60 mm SL juvenile) through Phase II (60 mm to 130 mm SL juvenile) production recirculating aquaculture systems included a nine-tank system and a ten-tank system. For the Phase II to Phase III (130 mm to 180 mm SL juvenile) production cycle, the red drum juveniles were cultured in larger replicated 4-tank RAS low-head systems. System design, operation, and water quality conditions were presented for each of the multi-tank systems.

MATERIALS AND METHODS

Phase I to Phase II Systems

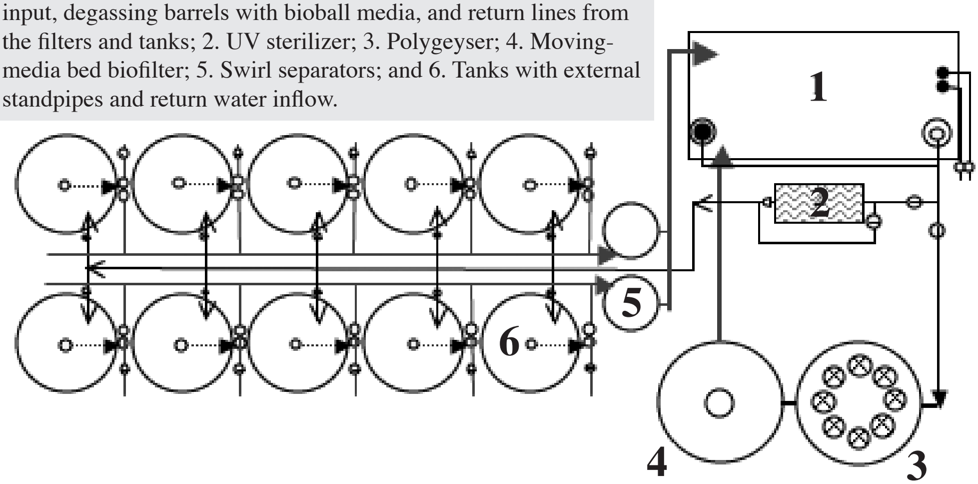
Low-head propeller pump system design (Figure 1)

The system consisted of ten round polyethylene tanks with a diameter of 1.52 m and a depth of 0.86 m for a total tank volume of 1.55 m^3 (Model no. TP440A, Aquatic Eco-Systems, Apopka, FL, USA). A 5.1 cm diameter bulk head fitting (Slip x FIPT) was installed in the center of each tank for drainage and connection to an external standpipe (5.1 cm in diameter) that controlled water height in the tank. The ten tanks were set up in two rows of five tanks with the outflow from each external standpipe connected to a 10.2 cm drain manifold for each row of tanks. The water from the drain line for each set of five tanks gravity-flowed into a 0.61 m diameter Wave Vortex filter (265 liters) (W. Lim Corporation, San Diego, CA, USA). Outflow from the two system vortex filters entered a 15.2 cm diameter PVC pipe manifold that drained into a rectangular 3.2 m^3 fiberglass sump (1.2 m wide x 2.4 m long x 1.1 m deep).

Water from the sump was returned to the tanks and transferred through the water treatment unit by a 1 hp submersible propeller pump (3 Phase, 220 V, 60 Hz; Model no. 125AB2.75, Tsurumi Manufacturing Co., Ltd, Japan). The low-head propeller pump supplied approximately 910 Lpm at

Figure 1. The low-head recirculating aquaculture system design for Phase I to II (25 to 60 mm) juvenile red drum production. The system uses a low-head propeller pump for water movement.

1. Sump with propeller pump, float valves for salt and freshwater input, degassing barrels with bioball media, and return lines from the filters and tanks; 2. UV sterilizer; 3. Polygeyser; 4. Moving-media bed biofilter; 5. Swirl separators; and 6. Tanks with external standpipes and return water inflow.



1.8 m of head. The water treatment unit consisted of a open polygeyser filter unit filled with approximately 0.6 m^3 of EN plastic floating media (International Filter Solutions, Marion, TX, USA) and a 0.71 m^3 moving bead biofilter with floating plastic Kaldness™ K1 structured media (Evolution Aqua, Lancashire, United Kingdom). The polygeyser and LSB filters (Clearwater Low-space Bioreactor, Aquatic Eco-Systems, Apopka, FL, USA) were placed in series and the water flow through the filters was on a continuous loop from and back to the sump at a flow rate of approximately 378.5 Lpm. Return water flow to the tanks was roughly 454 Lpm to provide each tank with a return flow rate of 38-45 Lpm. Thus, the tank turnover time was 0.6 hr or 1.6 tank turnovers per hour. The water flowed through a 10 bulb, 550-watt UV sterilizer (Model no. UV300-2, Aquatic Ecosystems, Apopka, FL, USA) before returning to the tanks. Any excess water flow from the pump (75 to 80 Lpm) flowed to a packed column unit filled with bio-ball polypropylene media material. Adequate oxygen concentration in the tanks was maintained by a continuous flow of liquid oxygen (7 Lpm) into a 0.2 m long, medium pore stone diffuser located in each tank and in the sump.

System maintenance

The tank center drains, the swirl separators, the polygeyser filter, and sump were purged to remove any settled solids. On a weekly basis, the center and external standpipes of the tanks were plunged with a scrub brush to remove any accumulated solids and minimize biofilm buildup that would hinder flow out of the tanks and into the drain manifold. The drain line was cleaned on an as needed basis with a rotary spray nozzle and pressure washer unit to minimize biofilm collection. The tank and sump sidewalls were brushed approximately every week. Settled solids accumulated on top of the polygeyser filter were vacuumed off as needed. Total system maintenance took approximately 10-15 hours weekly.

Hybrid low energy recirculation system design (Figure 2)

The hybrid system consisted of nine separate modules that incorporated a double drain fish culture tank (Waterline Ltd., Charlottetown, Prince Edward Island, Canada) paired to a torrus moving bed biofilter. The nine fiberglass tanks were 1.5 m in diameter and 0.9 m in depth for a total tank volume of 1.6 m^3. The double drain of each tank had a central sump 0.25 m in diameter and 9.1 to 15.2 cm deep. A 2.5 cm diameter drain line with

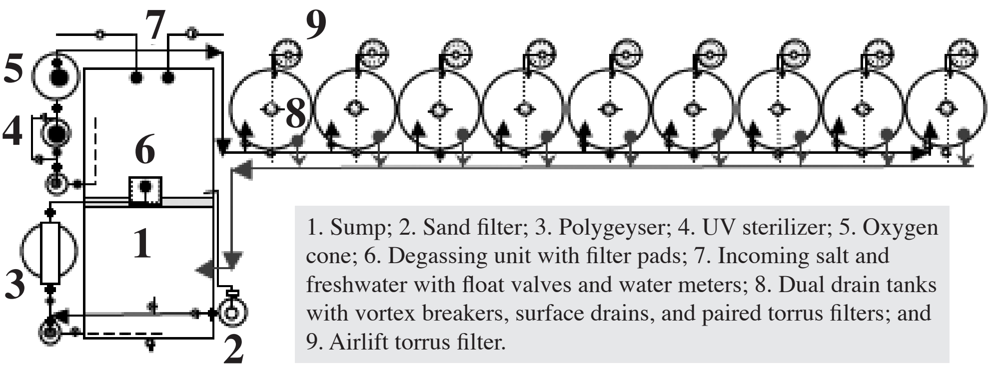


Figure 2. The low-energy hybrid recirculating aquaculture system design for Phase I to II (25 to 60 mm) juvenile red drum production. An airlift moves water between the tank and paired moving bed biofilter.

a ball valve from the center sump was used to purge the accumulated solids from the sump. A slotted 5.1 cm diameter standpipe was located in the center of the tank and the 0.95 cm wide slots were located in the upper portion of the standpipe. The center standpipe fit into a bulkhead at the bottom of the sump that was plumbed to the 7.6 cm diameter approach pipe of the torrus biofilter. Water from the tank was airlifted into the biofilter through the approach pipe by blowing air into the bottom of the pipe via a 1.9 cm diameter opening. Air for the Phase I to Phase II systems was supplied by a 3.5 hp, 3-phase regenerative blower (Model no. HRB-502, Republic Sales, Dallas, TX, USA). The torrus filters were filled with 0.11 m^3 of floating plastic Kaldness™ K1 structured media. The airlifted water flow through the filters with gravity flow back to the tanks was maintained at approximately 60 Lpm, providing a turnover time of the tank of roughly 0.44 hours or 27 minutes.

A secondary "polishing loop" was included in the system design for fine particulate filtration, oxygen supplementation, and UV sterilization. A 5.1 cm diameter bulkhead fitting was placed in the tanks for surface water removal and tank water height regulation. Surface water from the tanks drained into a 7.6 cm diameter return manifold, which was plumbed to the rectangular 3.2 m^3 fiberglass sump (1.2 m wide x 2.4 m long x 1.1 m deep). Plastic extruded netting, 0.6 to 1.3 cm mesh size, wrapped around the surface drain pipe was used to prevent fish mortalities or media from flowing into the drain manifold. Water from the sump was continuously recirculated through a 0.11 m^3 polygeyser filter and a 0.13 m^2 sand filter

(Model no. TA35, Aquatic Ecosystems, Apopka, FL, USA) via a 0.75 hp centrifugal pump (Model no. JP1, Aquatic Ecosystems, Apopka, FL, USA). Flow through each filter unit was approximately 110 Lpm. Water outflow from the polygeyser filter drops through a degas tower with four distribution plates that had either coarse or medium matala matting on top of the plate to remove fine particles before returning to the sump. Water from the sump passed through an 80-watt UV sterilizer (Model no. AST-80-2, Emperor Aquatics, San Diego, CA, USA), and a 170-liter oxygen injection speece cone (Waterline Ltd., Charlottetown, P.E.I., Canada) on the return to the tanks. Return water flow into each tank was controlled by a 2.5 cm ball valve and was approximately 35 Lpm, providing a turnover of the tank water of 45 minutes.

System maintenance

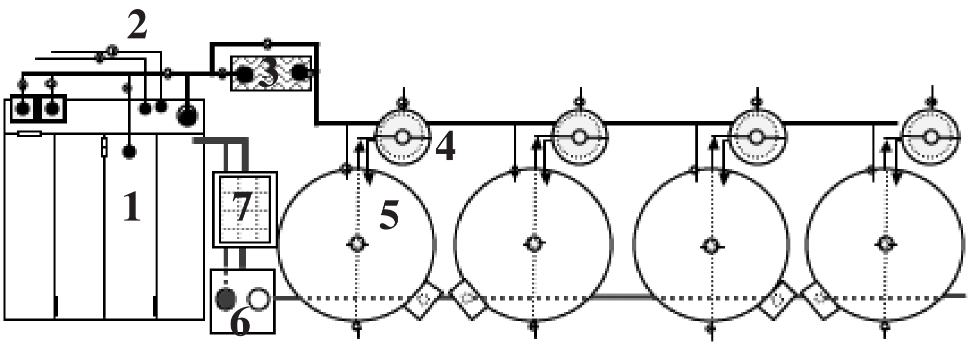
The polygeyser filter, torrus filters, sand filter, and sump were purged or backwashed daily for removal of accumulated and settled solids. The polygeyser was set to automatically backwash approximately every 4-6 hours by release of air in the air charge chamber of the filter. The matala filter pads were replaced daily with clean rinsed pads. On a weekly basis, the tank center standpipe and drain pipes were plunged with a scrub brush to remove any accumulated solids and minimize pipe biofilm buildup that would hinder flow out of the tanks and into the drain manifold. The drain line was cleaned as needed with a rotary spray nozzle and pressure washer unit. The tank and sump sidewalls were brushed weekly. Total system maintenance took approximately 10-15 hours weekly.

Phase II to Phase III Systems

Low-head propeller pump system design (Figure 3)

The system consisted of four dual drain, round fiberglass tanks 3.1 m in diameter and 1.1 m in depth for a total tank volume of approximately 7.8 m^3. A sump 0.38 m in diameter by 0.25 m deep was in the center of each tank. The sump was covered by a 7.6 cm diameter slotted standpipe with a PVC bottom plate allowing approximately a 0.6 cm gap around the sump. The plate also had radial 0.95 cm slots for water and solids to enter. The standpipe was fitted into a 7.6 cm diameter bulkhead at the bottom of the sump that was connected to the approach pipe of the tank side filter and provided mid-column water flow to the side filter. The side

Figure 3. The low-head recirculating aquaculture system design for Phase II to III (60 to >180 mm) juvenile red drum production. A low-head propeller pump for water movement from the sump to the tank and cross-counter flow oxygenator, air lift for water movement between the tank and paired moving bed torrus filters, and air for media movement in the sump.



1. Long flow pathway moving bed reactor with cross-flow oxygenator, float valves, and propeller pump; 2. Incoming salt and freshwater lines with float valves and water meters; 3. UV sterilizer; 4. Torrus filters with 0.37 m^3 of MB3 floating plastic media; 5. Three meter diameter tanks w/ center sump and sidebox drain; 6. Diverter box; and 7. Sixty micron screen rotary drum filter.

tank filter was a Wave Vortex filter (0.64 m^3; W. Lim Corporation, San Diego, CA, USA) filled with 0.37 m^3 of $MB^{3™}$ floating plastic media (WaterTek MB^3 Moving Bed Media, WMT, Baton Rouge, LA, USA). The media was continuously moving by a 0.23 m diameter air disc diffuser located under the media bed. Water in the approach pipe to the filters was airlifted to the surface of the filter by using air that flowed into a 1.9 cm diameter hole located near the bottom of the pipe. Air flow was 0.14 m^3/min and provided a water flow through the filters around 130 to 135 Lpm. The air lifted water flow was distributed across the top of the moving media bed of the filter bed and returned back to the tank by gravity. A 7.6 cm diameter PVC pipe with ball valve was plumbed into the tank sump to purge the accumulated solids from the sump. A 0.1 m^3 tank sidebox (0.3 m wide x 0.6 m long x 0.6 m deep) with a 7.6 cm diameter opening at the bottom was used for surface water removal from the tanks into a 15.2 cm diameter drain manifold. Surface water out of the sidebox flows to the system drum filter (Model 801, WMT, Baton Rouge, LA, USA). A 40 μm screen was used on the drum filter that was in line before the 11.3 m^3 sump (3.0 m x 3.0 m x 1.2 m deep). The custom fabricated sump was divided into five compartments, four of which held media (1.1 m^3 of $MB^{3™}$ media) and were aerated to keep the media moving. A remote drive regenerative air blower (3 Phase, 220V, 60 Hz; Sweetwater Model no. S51, Aquatic Eco-Systems, Apopka, FL, USA) supplied air to the six medium pore air diffusers located in each of the four compartments to provide an air flow of approximately 25 m^3/h for media movement. Water flowed through the four rectangular compartments (0.8 m x 2.4 m) before reaching the last compartment (0.6 m x 3.0 m). A 2 hp propeller pump (3 Phase, 220 V, 60 Hz; Model no. 125AB2.75, Tsurumi Manufacturing Co., Ltd, Japan) returned the water to the tanks. The propeller pump provided approximately 1500 Lpm against a total dynamic head of 2.4 m. An in-line programmable paddle wheel flow meter (Midwest Instrument & Controls Corporation, Rice Lake, WI, USA) monitored the total water flow returning to the tanks. An 8-bulb, 520 watt commercial size UV sterilizer (Model no. COM6520-Std, Emperor Aquatics, Inc., Pottstown, PA, USA) was used to disinfect all the return water to the tanks. A side-stream flow on the return line to the tanks supplied a low-head counter cross-flow (LHCCF) oxygenator with approximately 570-760 Lpm of water and the remaining flow returned to the tanks (760-910 Lpm). Liquid oxygen (LOX) flowed into the LHCCF oxygenator at 5-10 Lpm per unit. Each LHCCF tower was 0.6 m wide x 1.8 m high x 0.6 m deep. Water flow into the top of each tower was controlled by a 7.6 cm ball valve and flowed through four distribution plates before returning to the sump. Each 0.6 m x 0.6 m distribution plate had forty 0.95 cm holes for water dispersion. Liquid oxygen was injected into the tower at the bottom and passed through the plates in a zigzag counter flow pattern to the water flow. LOX volume into the towers was controlled by a flow meter with an adjustable valve. Additional LOX was added to the tanks using 30.5 cm ultra-fine bubble diffusers (Model no. AS303, Aquatic Ecosystems, Apopka, FL, USA) and controlled with 0 to 0.14 m^3/min acrylic flow meters.

System maintenance

The side tank moving bed filters were purged daily and the tank sumps were purged twice daily. System drain lines from the side box to the drum filter were cleaned with the pressurized rotary nozzle as needed. Return lines from the side filters were cleaned out twice weekly and more often if the gravity flow back into the tanks was observed to be restricted. Tank side boxes and the drum filter diverter box were scrubbed twice weekly for biofilm removal. Foam buildup in the moving bed biofilter/sump was removed daily. Tank scrubbings were conducted as needed and coordinated to minimize fish feeding disturbances. Maintenance for all four low-head systems was approximately 10-15 hours weekly.

Filter performance analysis

The volumetric total ammonia nitrogen conversion rate (VTR) was used as the principal indicator for evaluation of the filter performance. The VTR was obtained using the following equation:

$$VTR = K_C \times (TAN_{IN} - TAN_{OUT}) \times Q_F / V_{Media}$$

Where VTR is the g TAN removed per m^3 of filter media per day; Q_F is the flow rate through the filter (Lpm); K_C is the unit conversion factor of 1.44; TAN_{IN} and TAN_{OUT} are the influent and effluent total ammonia concentration in mg/L, and V_{Media} is the volume of the filter media in m^3.

Water quality analysis

Water quality in the systems was monitored daily. Measurements of pH, salinity, and temperature were taken from the sump or diverter boxes of the systems and the dissolved oxygen was measured in each individual tank. Measurements were done with a hand-held meter (YSI 556 MPS, Yellow Springs, OH, USA). Alkalinity of the systems was measured daily with a HACH test kit (Loveland, CO, USA) and maintained within the range of 150-200 mg/L $CaCO_3$ through the addition of sodium bicarbonate. Filter inlet and outlet water samples were collected for TAN and nitrite determination. Samples were analyzed immediately after collection using the HACH DR-2800 portable spectrophotometer and Method 8038 (Nessler method) for total ammonia determination and Method 8507 (Diazotization method) for nitrite determination. Flow rates were measured with an Ultrasonic Flow meter (PortaFlow SE model, Greyline Instruments, Messena, NY, USA) or by a bucket and stopwatch determination. Total suspended solids analysis of weekly water samples collected from the system sumps or diverter boxes were conducted in triplicate according to Standard Methods (APHA 1998).

RESULTS

Phase I to Phase II Systems

Low-head propeller pump system performance

This system has been in continuous operation with varying numbers and biomass loads since November of 2007. During that time the number of fish in each tank ranged from over 3500 per tank at initial stocking with a mean size of 4.0 g to a minimum of approximately 500 fish per tank with a mean weight of over 60 g. Fish biomass in the tanks ranged from 8.5 kg/m^3 at initial stocking to a peak of 62.3 kg/m^3 before reducing biomass by grading and transferring the larger fish to other larger systems. Daily feed rates per tank have been greater than 1.0 kg of feed per day (45% CP). Ambient water temperature has been at 24.6°C ± 1.3°C and system salinity, maintained by float valve control, in a range between 10 and 13 ppt. Total ammonia nitrogen ranged between 0.14 and 1.09 mg/L and nitrite-nitrogen was between 0.047 to 0.321 mg/L. System pH and alkalinity ranged between 7.0 and 8.0 and from 14 to 264 mg/L $CaCO_3$, respectively. Alkalinity in the system was maintained through the addition of sodium bicarbonate at approximately 0.25 kg bicarbonate per kg of feed. The average total suspended solids in the system were 8.6 + 4.2 mg/L. The minimum weekly measured TSS concentration value was 2.9 mg/L and the maximum weekly measured value was 18.5 mg/L. The maximum TSS value most likely corresponded to a period when the tanks or drain lines were being cleaned. The average daily system makeup water percentage was 7.1%. Water quality and system metrics are provided in Table 1 for this system during a 117 day production run for the Phase I to Phase II red drum juveniles.

The volumetric nitrification rate (VTR) of the polygeyser filter in the system averaged 77.4 + 37.2 g TAN / m^3 media-day during the production trial. The average VTR for the low space moving bed bioreactor was 38.9 + 29.3 g TAN / m^3 media-day. Graphs of the volumetric TAN conversion rates for the polygeyser and moving bead filters at varying influent TAN concentrations are presented in Figures 4 and 5, respectively.

System metrics	
Maximum fish density in culture tank (kg/m^3)	62.3
Mean turnover time:	
Culture tank	0.6 h
System volume through filtration units	0.95 h
Mean system exchange rate (% volume per day)	27.9%
Mean VTR for Polygeyser filter (g TAN / m^3-media-day)	77.4 ± 37.2
Mean VTR for LSB (g TAN/m^3 media-day)	38.9 ± 29.3
Water quality metrics	**Avg ± SD**
Temperature (°C)	24.6 ± 1.3
Salinity (ppt)	11.3 ± 0.5
Dissolved oxygen (mg/L)	9.2 ± 1.1
pH	7.3 ± 0.3
Alkalinity (mg/L $CaCO_3$)	199 ± 25
Total Ammonia Nitrogen, TAN (mg/L)	0.69 ± 0.18
Nitrite Nitrogen, NO_2-N (mg/L)	0.150 ± 0.055

Table 1. System and water quality metrics for the ten-tank low-head propeller pump recirculating aquaculture system used to culture red drum juveniles from Phase I to Phase II.

Hybrid low energy recirculation system performance

This system has been in operation with varying numbers and biomass loads since December of 2007. The number of fish in each tank has been as high as 3700 per tank at initial stocking with a mean size of 4.0 g and has varied depending on the grading needs. Four months after the initial stocking in December of 2007 the average number of fish per tank was approximately 500 with an average individual weight greater than 60 g. Fish biomass in the tanks ranged from 4.3 kg/m^3 at initial stocking to a peak of 54.1 kg/m^3 before grading and removal of the larger size fish. Daily feed rates per tank have been greater than 1.0 kg of feed per day (45% CP). The ambient water temperature of the system was 23.5°C ± 1.4°C. The range was larger because the system blower for airlift utilization was located outside and the outdoor air temperature had greater fluctuation than the indoor temperature. Salinity was between 6.4 and 14.2 ppt and was controlled by setting the flow of water coming through the make-up water float valves. Total ammonia nitrogen ranged

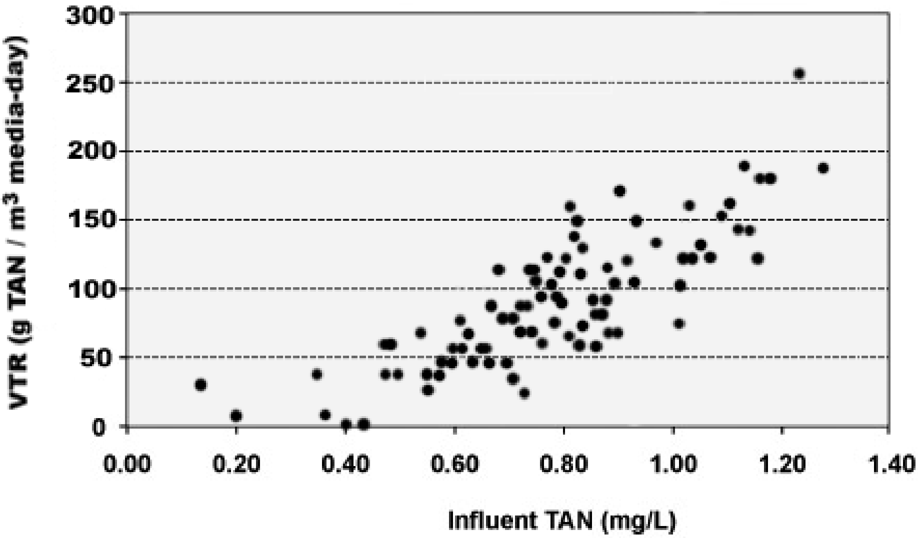


Figure 4. Volumetric nitrification rate (VTR) for a polygeyser filter with 0.57 m^3 of EN media utilized in the low-head recirculating aquaculture system for Phase I to Phase II (25 to 60 mm) red drum fingerling production. (N=94)

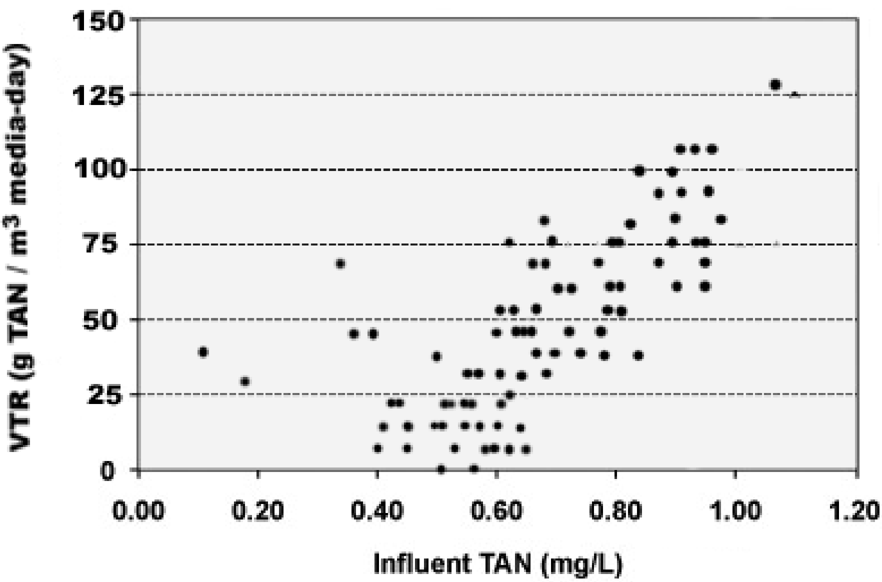


Figure 5. Volumetric nitrification rate (VTR) for a moving bead biofilter with 0.71 m^3 of floating plastic Kaldness K1 media utilized in the low-head recirculating aquaculture system for Phase I to II (25 to 60 mm) red drum fingerling production. (N=94)

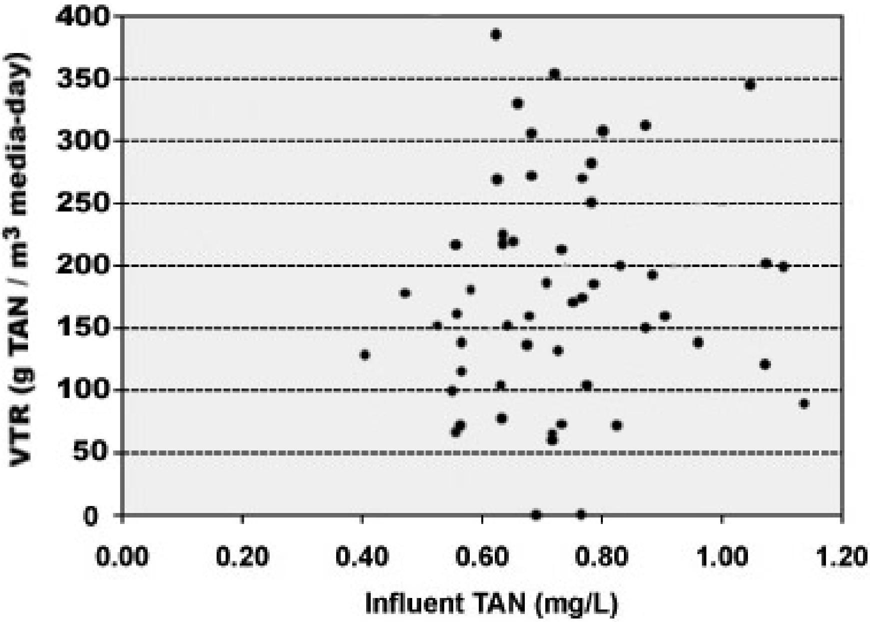


Figure 6. Volumetric nitrification rate (VTR) for a polygeyser filter with 0.11 m^3 of crimped floating plastic media utilized in the low-energy hybrid recirculating aquaculture system for Phase I to II (25 to 60 mm) red drum fingerling production. (N=56)

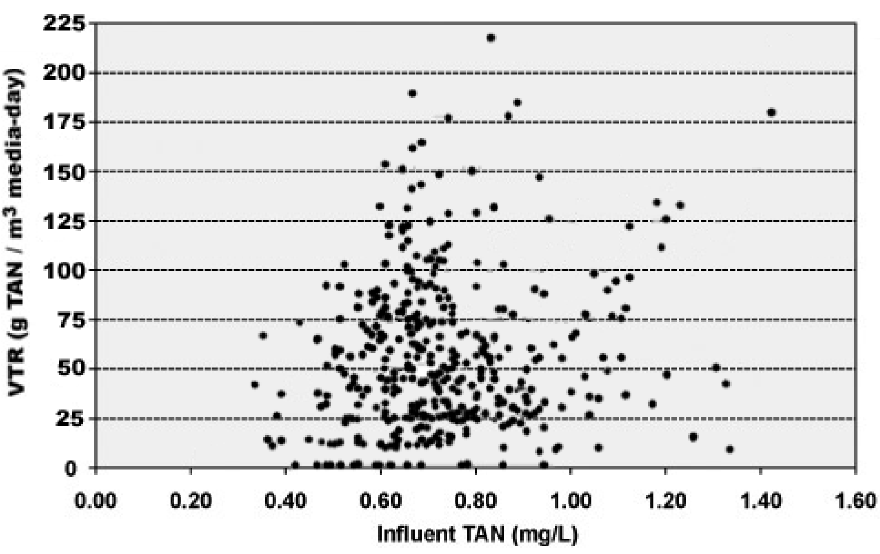


Figure 7. Volumetric nitrification rate (VTR) for the moving bed torrus filters with 0.11 m^3 of Kaldness media utilized in the low-energy hybrid recirculating aquaculture system for (Phase I to II mm) red drum fingerling production. (N=419)

System metrics	
Maximum fish density in culture tank (kg/m^3)	54.1
Mean turnover time: Culture tank System volume through filtration units	 0.75 h 2.6 h
Mean system exchange rate (% volume per day)	12.5%
Mean VTR for Polygeyser filter (g TAN / m^3-media-day)	181.1 ± 88.9
Mean VTR for LSB (g TAN/m^3 media-day)	56.5 ± 36.7
Water quality metrics	**Avg ± SD**
Temperature (°C)	23.5 ± 1.4
Salinity (ppt)	11.5 ± 1.0
Dissolved oxygen (mg/L)	8.2 ± 1.1
pH	7.6 ± 0.1
Alkalinity (mg/L $CaCO_3$)	218 ± 29
Total Ammonia Nitrogen, TAN (mg/L)	0.74 ± 0.18
Nitrite Nitrogen, NO_2-N (mg/L)	0.415 ± 0.279

Table 2. System and water quality metrics for the nine-tank hybrid low energy recirculation aquaculture system for culturing red drum juveniles from Phase I to Phase II.

between 0.2 and 1.4 mg/L and nitrite-nitrogen was in the 0.020 to 1.590 mg/L range. System pH was usually in the 7.1 to 7.7 range as the air input to the torrus filters and degas towers helped keep the CO_2 concentration to a minimum in the system. Alkalinity was maintained at approximately 218 mg/L $CaCO_3$ by daily sodium bicarbonate additions. The average total suspended solids in the system was 10.9 ± 4.9 mg/L. The minimum weekly measured TSS concentration value was 5.4 mg/L and the maximum weekly measured value was 24.3 mg/L. The maximum TSS value corresponded to a period when the tanks or drain lines were being cleaned. The average daily system makeup water percentage was 8.3%. The average volumetric nitrification rate for the 0.11 m^3 polygeyser filter was 181.1 ± 88.9 g TAN /m^3 media-day. The average VTR for the side tank moving bed torrus filters of the system was 56.5 ± 36.7 g TAN / m^3 media-day. Graphs of the VTRs for the polygeyser and torrus filters with a range of influent TAN concentrations are presented in Figure 6 and Figure 7, respectively. Metrics for the system and the water quality during the production run are presented in Table 2.

Phase II to Phase III Systems

Low-head propeller pump system performance

The first of four of these systems (System A) was completed and all four tanks stocked with Phase II red drum juveniles in early March 2008. The second system (System D) was stocked with juveniles in late March 2008 and construction of a third system was completed and stocked with juveniles in June 2008. All three systems were stocked with 250 kg of red drum juveniles, weighing over 100 g each, in each tank. System A had a maximum biomass of 42.6 kg/m^3, System C maximum biomass was 50.8 kg/m^3, and System D had a maximum biomass of 48.3 kg/m^3 during the production runs. The water temperature was between 26 and 29°C for the three systems and was dependent on the outside air blowers that supply air for the moving bead and torrus filters. Salinity of the system was maintained between 11 and 13 ppt. Total ammonia nitrogen was under 1.5 mg/L and nitrite-nitrogen under 0.5 mg/L. System pH was above 7.0 as the air input to the moving beds and torrus filters minimizes CO_2 buildup in the system. Alkalinity was maintained over 250 mg/L $CaCO_3$ by daily dosing with sodium bicarbonate. The average total suspended solids concentrations in System A and System D were 5.2 ± 1.8 mg/L and 7.5 ± 1.4 mg/L respectively. The minimum weekly measured TSS concentration value was 1.9 mg/L and the maximum weekly measured value was 11.2 mg/L. The maximum TSS value corresponded to a period when the tanks or drain lines were being cleaned. The percent of daily makeup water for the systems in operation ranged from 7.2 ± 4.3% to 12.1 ± 7.3%. The amount of makeup water was dependent on the number of fish in the system and the number of tanks in each system with fish.

The average volumetric nitrification rate of the long flow pathway moving bead biofilter for System A was 59.5 g TAN/m^3 media-day (SD = 23.7) with a maximum rate of 152.9 g TAN/m^3 media-day. The average volumetric nitrification rate of the biofilter for System D was 62.2 g TAN/m^3 media-day (SD = 22.2) with a maximum rate of 123.7 g TAN/m^3 media-day. Volumetric nitrification rates for the side torrus filters on System A and D were 48.2 ± 27.4 and 87.0 ± 22.0 g TAN/m^3 media-day, respectively. The maximum VTR for the torrus filters on System A was 103.7 g TAN/m^3 media-day with an influent TAN concentration of 0.93 mg/L. The maximum VTR for System D torrus filter was 125.9 g TAN/m^3 media-day when the influent TAN concentration was 1.25 mg/L. The torrus filters on both systems showed low VTRs for a range of influent

Table 3. System and water quality metrics for the low–head recirculation aquaculture system for culturing red drum juveniles from Phase II to Phase III.

		System A	System C	System D
System metrics	**Units**			
Culture period	days	142	57	127
Maximum fish density in tank	kg/m^3	42.6	50.8	48.3
Mean turnover time:				
Culture tank	Hour		0.62	
System volume through filtration units	Hour		0.84	
Mean system exchange rate	% vol/day	9.8 ± 8.0	7.2 ± 4.3	12.1 ± 7.3
Mean VTR for Long path moving bed biofilter	g TAN/ m^3-media-d	59.5 ± 23.7		62.2 ± 22.2
Mean VTR for Torrus moving bed biofilter	g TAN/ m^3-media-d	48.2 ± 24.4		87.0 ± 22.0
Water quality metrics		**Average ± SD**		
Temperature	°C	26.3 ± 1.6	28.5 ± 0.9	27.2 ± 1.4
Salinity	ppt	11.7 ± 0.6	11.5 ± 0.9	11.8 ± 0.8
Dissolved oxygen	mg/L	112.2 ± 9.8	118.7 ± 11.6	110.5 ± 10.8
pH		7.2 ± 1.5	7.7 ± 0.3	7.5 ± 0.7
Alkalinity	mg/L $CaCO_3$	250 ± 46	266 ± 28	258 ± 30
Total Ammonia Nitrogen, TAN	mg/L	0.35 ± 0.11	0.64 ± 0.76	0.39 ± 0.12
Nitrite Nitrogen, NO_2-N	mg/L	0.647 ± 0.733	0.500 ± 0.153	0.860 ± 0.768

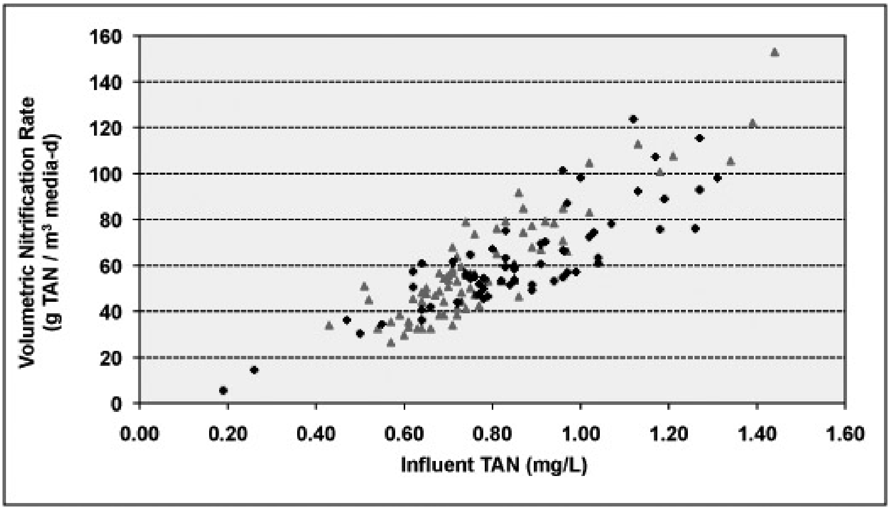


Figure 8. Volumetric nitrification rate (VTR) for a long flow pathway moving bed biofilter with 4.5 m^3 of MB^3 floating plastic media at varying TAN influent concentrations that was utilized in a low-head recirculating aquaculture system for Phase II to III (60 to > 180 mm) red drum fingerling production. Gray triangles represent the VTRs for System A biofilter and black diamonds represent the VTRs for System D biofilter.

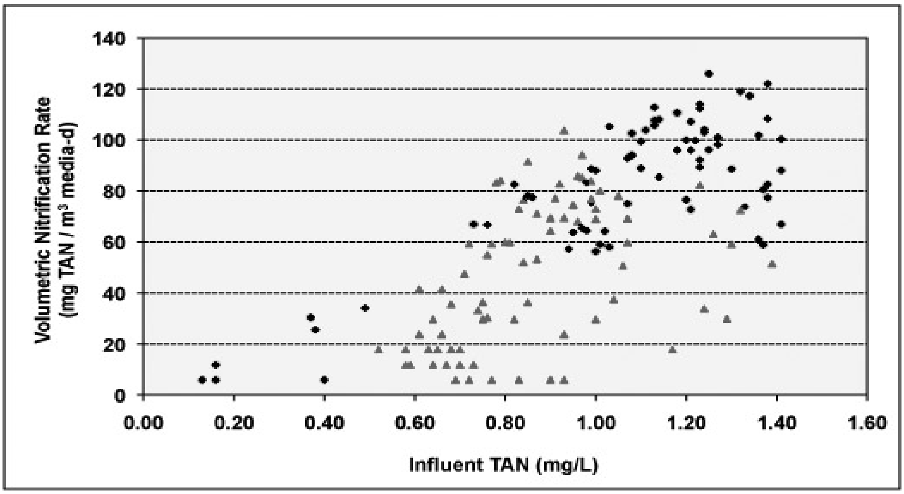


Figure 9. Volumetric nitrification rate (VTR) for the torrus filters with 0.37 m^3 of MB^3 floating plastic media utilized in the low-head recirculating aquaculture system for Phase II to III (60 mm to > 180 mm) red drum fingerling production. The volumetric nitrification rates for each torrus filter were determined for varying concentrations of influent total ammonia nitrogen (TAN) concentration. Red triangles represent System A torrus filter VTRs and black diamonds represent System D torrus filter VTRs.

TAN concentrations between 0.40 to 0.93 mg/L. Volumetric nitrification rates for the biofilters in System C were not collected during this trial period. The system and water quality metrics for the three low-head systems in operation are presented in Table 3. A graph of the VTR for various influent TAN concentrations for the long flow pathway moving bead biofilter of System A and D are presented in Figure 8. The VTR for various influent TAN concentrations for the side filters of System A and D are presented in Figure 9.

DISCUSSION

It should be emphasized that the volumetric nitrification rates (VTR) for the biofilters of the various systems presented do not represent complete nitrification rates to nitrate but only ammonia oxidation rates. These rates are useful for designing systems and allow one to determine the effective volume of biofilter media required to maintain a desired ammonia concentration dependent on the remaining engineering and management of the system. The observed VTR numbers for the biofilters were on the low end of the performance range. Biofilter nitrification rates are influenced by the organic load, the dissolved oxygen concentration of the filter water, the influent TAN concentration, temperature, the pH and alkalinity, and the previous history of the biofilm (Zhu and Chen 2001, Ebeling and Wheaton 2006, Michaud *et al*. 2006, Rusten *et al*. 2006). The low nitrification performance of the filters however, can be attributed to the salinity of the system. Nitrification rates of biofilters in seawater systems are generally lower than in freshwater systems (Otte and Rossenthal 1979, Nijof and Bovendeur 1990, Rusten *et al*. 2006).

The measured VTR values for the 0.71 m^3 moving bed biofilter of the Phase I-II system were 30-40 percent of values reported for freshwater aquaculture applications. The 0.11 m^3 moving bed torrus filters showed slightly better results but the VTRs varied wildly. This variation can be a result of the different feed rates to each of the tanks because of the different stocking densities or fish size, different water flow rates through the filters, and different aeration rates for media movement. In a moving bed reactor the ideal biofilm is thin and evenly spread over the media surface as substrate penetration (ammonia metabolites) is usually less than 100 μm. Thus, aeration of the filter media is of importance to maintain a thin biofilm on the media by shear forces, allowing diffusion transport of dissolved oxygen and ammonia ions to the nitrifying bacteria layered in the media biofilm. The low nitrification rates observed may have been a result of the aggressive aeration of the media in the moving bed biofilters in addition to the saltwater environment. Aggressive aeration of the media results in over shearing of the media biofilm and limits the protective media surface area required for adequate nitrifying bacterial growth. In the long flow moving bed biofilter the filling fraction of the media in the reactor was 70%. Lower filling fractions in the range of 40 to 60% are recommended and as a result the media may have been substrate (ammonia) limited. Future studies are planned to evaluate an appropriate filling fraction of media in the long flow pathway reactor.

Nitrification of submerged plastic media biofilters for aquaculture applications has been thoroughly studied (Malone *et al.* 1993, De Los Reyes and Lawson 1996, Malone *et al.* 1999, Malone and Beecher 2000, Pfeiffer and Malone 2006). However, there is little information regarding nitrification performance of the polygeyser filters, especially in marine or brackish water aquaculture applications. The polygeyser is a submerged plastic media biofilter where the air chamber of the filter allows for frequent media air scrubbing backwashes each day. Increasing the backwashes reduces the back pressure of the filter due to particle entrapment and enhances the nitrification abilities of the filter media (Golz *et al.* 1999). The 0.57 m^3 polygeyser filter was set to backwash every 6 hours and the 0.11 m^3 polygeyser was set to backwash every 4 hours. Both units were primarily used as solids capture devices rather than biofiltration units. The polygeyser units provided higher nitrification rates than the moving bed biofilters, but the VTRs were still significantly lower than freshwater submerged media nitrification rates at comparable influent TAN concentrations (Ebeling and Wheaton 2006). The variability in the smaller polygeyser nitrification rate was most likely due to the variability of the sampling event with timing of the filter backwashing.

The Phase I to II systems implemented swirl separators, filter pads, sand filters, in-tank sump purging, and polygeyser filtration in an effort to reduce and minimize the solids load in the systems. The Phase II to III systems utilized 40 micron rotary drum filters as the primary solids removal mechanism. These mechanical methods were employed in an effort to reduce the solids load on the system, but an observed accumulation of fine particles in the system culture water was still observed, which limited increased density loads and production from these systems. Future design consideration and evaluation should include the use of foam fractionation equipment with ozone to reduce the concentration of fine particles accumulating in the systems.

Our investigation and evaluation is an attempt to determine the usefulness of filtration equipment, both mechanical and biological, for low-head recirculating aquaculture systems used for inland culture of marine species. The systems presented indicate that inland culture of marine species for commercial aquaculture production or stock enhancement purposes is possible even under the technical constraints presented. The percent survival of red drum juveniles from Phase I to III in these systems was over 70%, the food conversion ratio was 1.02, and no diseases were detectable during the production run. The goal is to improve the efficiency of the low-head system design and reduce the energy, water, and supplemental oxygen usage of these systems, while increasing the culture capacity the system can effectively sustain.

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