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Design of a novel recirculating aquaculture system for muskellunge rearing

Abstract

The adoption of Recirculating Aquaculture Systems (RAS) technology is occurring worldwide. This paper describes the creation of a unique RAS system used for rearing muskellunge *Esox masquinongy*. The recirculating aquaculture system described in this paper is comprised of five 2.44-meter diameter dual-drain tanks, a drum filter, ultraviolet sterilization unit, carbon dioxide degassing tower, 5-ton split unit heat pump, a pressurized bead filter (PBF), and a nano bubbler. A fixed speed 1.5 horsepower pump circulated water at a rate of 0.738m^3/min throughout the main pumping loop, and a fixed speed 0.75 horsepower pump circulated water in the side loop at rate of 0.51m^3/min. While this design worked, issues, particularly with water flows during certain events, occurred. Solutions to alleviate these problems and improve rearing efficiencies are described.

Keywords: RAS, recirculating aquaculture, muskellunge, *Esox masquinongy*

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Introduction

Muskellunge *Esox masquinongy* are a large freshwater fish endemic to North America.[1] They are a popular sport fish with recreational anglers, but natural recruitment is limited, leading to declining populations throughout their native range.[2-5] Thus, many muskellunge populations are maintained by the stocking of hatchery-reared fish.[6,7]

Historically, juvenile muskellunge were typically reared extensively in earthen rearing ponds, feeding on naturally produced zooplankton before transitioning to minnows or other fish released into the pond.[8-10] More recent techniques have involved training larval muskellunge to accept formulated feeds during intensive rearing.[11,12] These traditional rearing strategies have been limited by temperature constraints. Ideal water temperatures for muskellunge growth during hatchery rearing are from 20–24°C.[13-15] In temperate climates, fish are typically produced when pond water or surface water used during intensive rearing are at the optimum temperature for only a few months each year. Manipulating the temperature in single-pass water used only once during hatchery rearing is extremely expensive.[16,17] With the post-stocking survival of muskellunge positively related to the size of fish stocked,[12,18,19] producing the largest fish possible in the shortest amount of time is essential for successful hatchery operations. The use of Recirculating Aquaculture System (RAS) technology is very well suited to meet this need.

As the name implies, Recirculating Aquaculture Systems continually re-use hatchery production water, with the water treated by a series of processes.[20] RAS units generally consist of components to remove solid waste from fish and uneaten feed,[21,22] ammonia-detoxifying biofilters,[23,24] carbon dioxide strippers,[25] oxygen generators and injectors,[26] heater/chillers for temperature control,[27] and ozone or ultraviolet radiation for microbial control.[28-30] Thus, RAS greatly reduces the expense of heating or chilling.[16,17,31] The use of RAS also improves biosecurity by reducing the risk of fish pathogens and aquatic invasive species introduction during hatchery rearing.[32,33] In addition, because of the limited water inputs and discharge inherent to RAS, environmental impacts and geographic limitations on hatchery location are greatly reduced.[34,35]

There are few commercially available complete RAS units, with nearly all systems custom designed and constructed.[36,37] This manuscript describes an innovative RAS system used for the rearing of muskellunge and other fish species, along with recommendations for future improvement.

System overview

The recirculating aquaculture system described in this paper is comprised of five 2.44-meter diameter tanks, a drum filter, ultraviolet sterilization unit, carbon dioxide degassing tower, 5-ton split unit heat pump, a pressurized bead filter (PBF), and a nano bubbler. A fixed speed 1.5 horsepower pump circulated water at a rate of 0.738m^3/min throughout the main pumping loop, and a fixed speed 0.75 horsepower pump circulated water in the side loop at rate of 0.51m^3/min. The components of this system are listed in Table 1.

Culture tanks

Each 2.44-m diameter circular culture tank had an operational depth of 0.762 m and a working volume of 3.56m^3. Tanks were dual-drain,[38,39] with a centrally located 61-cm x 61-cm sump and a 46-cm side drain. The sump had a 5cm hole in the middle for the bottom drain. A 45-L Radial Flow Settler (RFS)[40] was bolted to the side drain of the culture tank (Figure 1). Effluent from the center drain was routed into the RFS, where settleable solids (>200 microns) are captured and removed once daily. In the center drain hole, a fitting was molded into the tank construction to ensure a positive connection with a drainpipe. Under optimal conditions, 10-to-20% of incoming flow exited through the bottom of the culture tank.[41] This flow contained up to 90 percent of the solids. The remaining 80-to-90 percent of tank flow exited through the side drain (Figure 2).

Table 1 Recirculating Aquaculture System components

Quantity	Component	Manufacturer	Model
1	Main Pump	PerformancePro	A2-1 ½-HF
1	Side-loop Pump	PerformancePro	A2-3/4-HF
1	Drum Filter	Profidrum	Eco 60/60
1	Biofilter	AST Polygeyser	HPPG 25 bubble bead
1	Heater/Chiller	Delta Hydronics	5-ton split unit
1	CO^2 Stripper	Self	1.02 M^3 degassing media
1	O^2 Injector	Gaia	UFB 300 nannobubbler
5	Tanks	CF Maier	2.44-m diameter fiberglass
1	Air Compressor		
1	Make-up Water Pump	Barracuda	0.75 hp Dual Application
1	Sump pump	Pentair	0.33 hp
1	Barrel		114 L

Figure 1 Radial flow settler (RFS) bolted to the side of the culture tank.

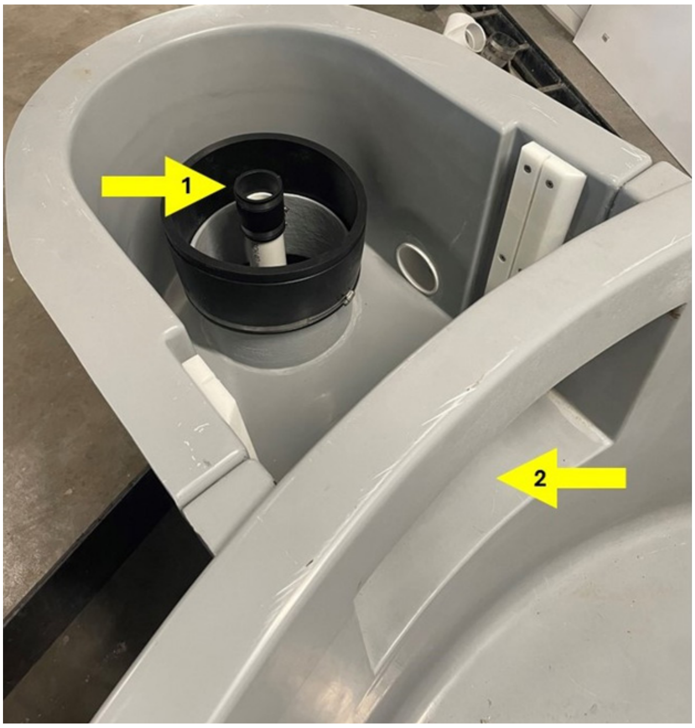

Figure 2 Effluent point from the central drain (1), and remaining tank effluent route (2).

Water inlet

Water was directed into each tank via a spraybar with a horizontal pipe and vertical section (Figure 3).[42] Both sections of the spraybar were threaded to a Tee to allow for individual adjustment to optimize tank rotation. Spraybar sections were constructed of 50.8-mm schedule 40 Poly Vinyl Chloride (PVC) pipe, with seven 25.4mm holes drilled in series. To increase tank rotational velocities if needed, each spraybar section could be replaced with another set with 12.7mm holes. Observations indicated that with comparable flows, smaller apertures in the spraybar sections increased tank rotational velocity and improved hydraulic self-cleaning. This is likely because of the increased outgoing pressure produced by the smaller openings, as per the Bernoulli effect.[43]

Drain structure

A single 50.8-mm diameter PVC pipe was fitted into the hole in the center of the tank sump (Figure 4). A series of holes were drilled into the bottom of the drainpipe to capture waste and prevent fish escapement. The size of pipe holes was dependent on life stage and ranges from 3.2mm to 25.4mm. The drainpipes were not glued into the tank fitting but were instead press-fitted to allow for quick and convenient exchange.

Solids management

Settleable solids (200 micron and larger) were trapped in the RFS of each tank. Treated discharge from the RFS combined with the water exiting the side drain of each culture tank (Figure 5). After exiting radial flow settlers and side drains, all flow passed through a drum filter with 70-micron screen (Figure 6). The drum filter had a maximum flow rating of 1.09m^3/min. It had four 100-mm exit ports on both the treated and untreated section to provided flexibility for water routing. After the drum filter, water passed through a bead filter to further filter solids down to 10microns (Figure 7).[41]

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Figure 3 Tank spray bar.

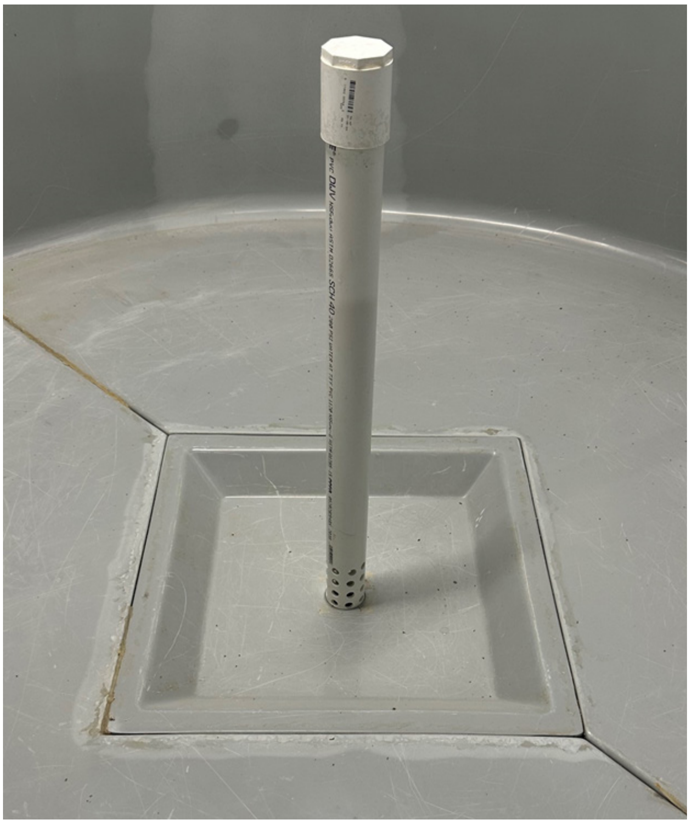

Figure 4 Center drainpipe in tank sump.

Figure 5 Combined effluents of the culture tank exiting the side drain structure.

Figure 6 Drum filter with 70-micron screen.

Bio-filtration

In addition to filtering solids, the PolyGeyser bead filter also served as the biofilter responsible for nitrification.[44,45] The bead filter was equipped with an air compressor that triggered a periodic agitation of the bead media (Figure 8). During each agitation event, waste was dislodged from the beads and settled into a chamber at the bottom of the unit. A valve protruding from the sludge chamber was periodically opened to evacuate dislodged waste from the unit. Frequency of agitation events became greater as the overall system load increased. If agitation events became too infrequent, nitrification efficiency greatly decreased, and water outflow from the bead filter was reduced.

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Figure 7 Pressurized bead filter.

Figure 8 Air compressor on the pressurized bead filter to initiate agitation cycles.

Carbon dioxide degassing unit

A counterflow degassing tower design was used to remove carbon dioxide.[46] Aluminum framing and 1.2 x 2.4m sheets of black High-Density Polyethylene (HDPE) panes were used to construct the tower. The HDPE panels extended below the packed media section of the tower and submerged into a collection basin to form a seal for atmospheric air forced into the tower. The entire structure had the following dimensions: 1.47m x .97m x .86m. The system was designed for projected maximum feeding rates, requiring 0.76m^3 of bio-media to achieve a surface area-to-volume ration of 226m^2/m^3. The relatively high bio-media surface area provided a secondary benefit of nitrification.[47] The tower was packed with four layers of media (Model CF1200, LS Enterprise LLC, East Earl, Pennsylvania, USA) each with a depth of 30.5cm. The top of the tower had a manifold leading to four spray nozzles that evenly distributed water across the media (Figure 9). Total pumping volume was approximately 0.492m^3/min distributed across an area of 0.62 m^2, resulted in a hydraulic loading of 0.79m^3/m^2. For gas transfer, a 10.9m^3/min blower supplied air at the bottom of the tower and expelled exhausted air from the top of the tower (Figure 10). The gas to liquid ratio for the operating tower was projected to be approximately 22:1. A 1250-L Intermediate Bulk Container (IBC) tote served as the collection basin for water being pumped through the tower (Figure 11). The exhausted air was vented from the top of the tower to an existing sewer vent for evacuation from the building.

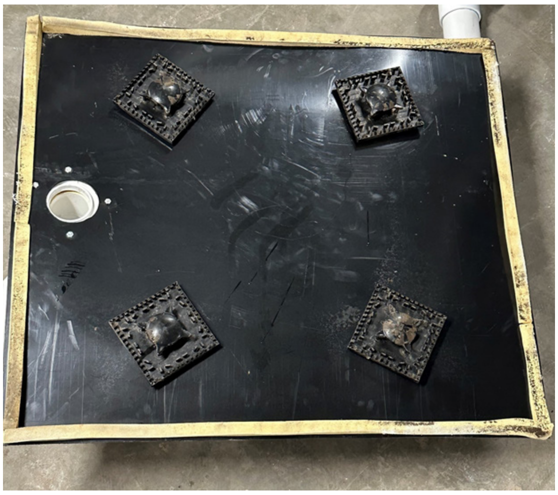

Figure 9 Spray nozzles for the carbon dioxide degassing tower.

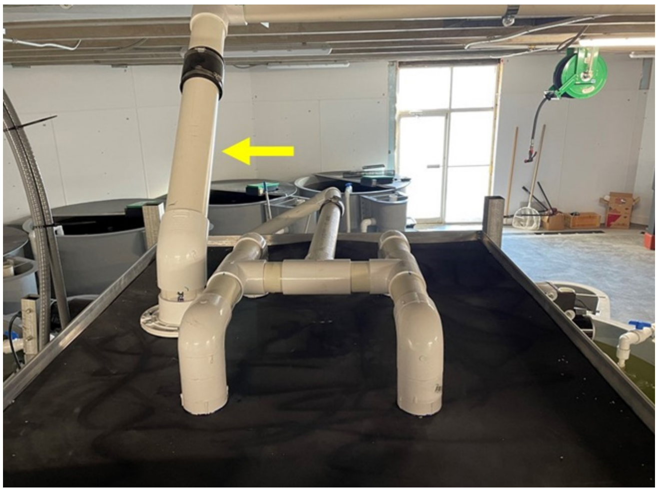

Figure 10 Carbon dioxide vent coming out of the carbon dioxide degassing tower.

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Figure 11 Front of degassing tower with the intermediate bulk container used as collection vessel.

Oxygenation

A nano bubbler with the capacity of 41.16kg of oxygen per day at approximately 80 percent efficiency was incorporated into the main system pump line for oxygenation.[48] The size of the nano bubbler used was needed to prevent unacceptable flow restriction to the culture tanks, thereby allowing for main pumping line integration and eliminating the need for an additional side-loop pump. Pure oxygen was supplied to the unit through an adjustable flow meter at 2.07 bar from a bulk liquid oxygen tank located outside of the building (Figures 12&13). The nano bubbler was rated at 80% efficiency for flow rates of approximately 1.14m^3-to- 1.89m^3 per minute. Main line flow was approximately 0.76m^3, resulting in less than 80% gas transfer efficiency.[49] This sub-optimal gas transfer efficiency was acceptable because maximum system loadings require less than 41.16 kg of oxygen per day.

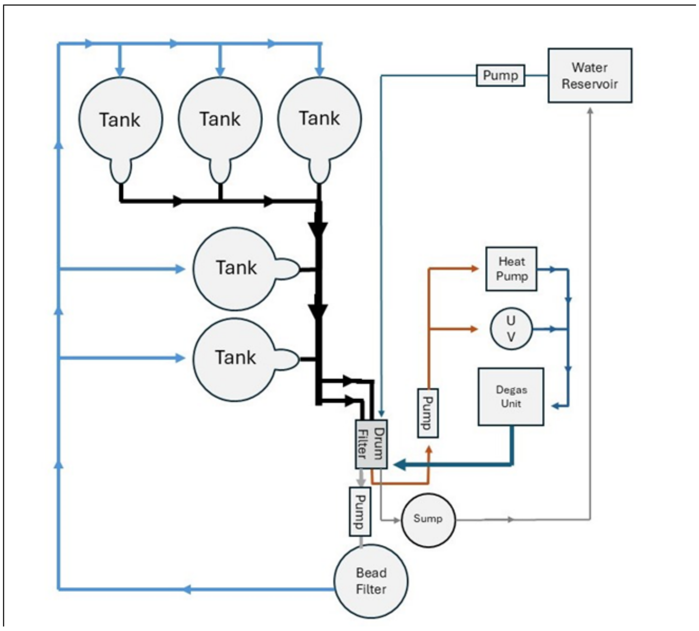

Figure 12 Diagram of water flow throughout the recirculating aquaculture system.

Figure 13 Oxygen bulk tanks.

Temperature control

For temperature control, water was pumped on a side loop from the drum filter tank to a heat pump and then routed to the sprayer

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manifold for the carbon dioxide degassing tower. Initially, an Aquacal SQ166r heat pump (Aquacal, St. Petersburg, Florida, USA) was used. This unit was located inside the building and required the construction of a fume hood to collect and move the exhausted air outside the building. To eliminate the need for a hood, the initial heat pump was replaced with a 5-ton split unit (Delta Hydronics, Bolton, Florida, USA). The new unit was able to manipulate water temperature 10º C from ambient air temperature (approximately 20-to-23C) at rate of 1º C per hour and expelled the discharged air outside of the building. The split unit greatly increased the efficiency of the Heating, Ventilation, and Air Conditioning (HVAC) system in the building and greatly reduced background noise.

Water flow

Figure 12 is a diagram showing the flow of water through the RAS system. The life support loop of water was continuously pumped from the treated section of the drum filter through the nano bubbler for oxygenation, and into the Polygeyser biofilter at an approximate rate of 0.73m^3/min. The water exited the biofilter to the culture tanks. After a target hydraulic retention time of 30 minutes in the tanks, water returned to the untreated section of the drum filter. A secondary loop was also continuously pumped at a rate of 0.492m^3/min from the treated side of the drum filter. It was diverted evenly to the heat pump and the ultra-violet sterilizing unit. After passing through each treatment device, the water combined into a common line and flowed to the carbon dioxide degassing tower. After passing through the degassing tower, the water was collected in a basin and flowed back to the treated side of the drum filter where it assimilated with the main pumping line of flow.

Ultraviolet sterilization

Treated effluent was pumped from a 100mm port on the drum filter to a SITA UV AM 50 UL 440-watt ultraviolet sterilization unit (SITA Srl, Genoa, Italy) at a rate of approximately 0.26m^3/min. This flow rate ensured that the entire volume of the recirculating system was treated the number of times per day[50] needed to achieve an ultraviolet (UV) sterilization dose of 30mJ/cm^2 [28] so that microbial levels were maintained at acceptable levels.

Pipe sizing

The main water supply line was constructed of 76.2-mm schedule 40 solid core PVC pipe. At the junction of each tank, it was reduced to 50.8mm prior to entering the tank. The velocity of the main supply line exceeded 2.14 meters/sec. The drain line was 101.6-mm schedule 40 PVC pipe for the effluent of the first two culture tanks and increased to 152.4-mm schedule 40 PVC where effluent from the third tank entered the drain line. It remained at 152.4-mm until adapting to the 101.6-mm drum filter connections.

Make-up water

Any water lost was replenished from a 2,290L reservoir constructed of two IBC totes vertically stacked (Figure 14). The capacities of the bottom and top totes were 1,250L and 1,040L, respectively. Both containers were twinned to serve as one singular unit. A float valve in the top container allowed the reservoir to fill with dechlorinated municipal water as needed. A water supply line from the reservoir was routed to the intake of a booster pump (Barracuda Pumps, Minneapolis, Minnesota, USA). The outflow of the booster pump was then routed to the untreated section of the drum filter, where a float valve was installed[51]. Any water lost during cleaning operations lowered the water in the untreated section of the drum filter, subsequently lowering the float valve. When the float valve was lowered past the pre-determined set point, the booster pump was activated, supplying water from the reservoir at approximately 56L/min.

Figure 14 Stacked IBC water reservoirs.

Figure 15 Float valve installed on the influent side of the drum filter.

Water reduction methodology

Water was lost from the system because of evaporation and cleaning activities.[52] During initial testing, loadings of approximately 400kg of fish resulted in daily water loss quantities approaching 20-to-25%. Operation of the Polygeyser bead filter at agitation intervals of approximately 120-180minutes displaced an estimated 475L of water per agitation event. As the biomass loads increased and biofilter agitation events became more frequent, unacceptable water losses occurred. A daily water exchange rate of 5% was determined optimal.[53] To achieve the lower daily water exchange rate, a standpipe was installed in the treated section of the drum filter to regulate the maximum allowable operating height of the drum filter (Figure 16). Any displaced water from the standpipe flowed to a 113.5L barrel containing a sump pump (Figure 17) When enough water was collected in the barrel, a float switch activated the sump pump, and water was pumped to the water storage reservoir to be used as replenishment water. After installing the standpipe and optimizing its level, daily water exchange rates were reduced to under 5%.

Figure 16 Standpipe governing maximum water level on the treated effluent side of the drum filter.

Figure 17 Sump barrel used to collect overflow from the drum filter standpipe.

System improvements

The RAS described in this paper has operated continuously for over two years. Successful rearing occurred with fish rearing densities of <85kg/m^3. Despite this success, several problematic areas in need of improvement were identified. Specific problems included:

i. No water flow during a bead filter agitation event.
ii. Compromised mainline flow through the bead filter during air-assisted backwash.
iii. Vulnerable and complex water replenishment logistics.
iv. Low efficiency of temperature control.
v. Inadequate pumping of reserve water.
vi. Lack of pumping flexibility and control.
vii. Undersized pipes for both treated water and drain lines.
viii. Lack of bypass infrastructure for the drum filter.
ix. Mediocre occupational ergonomics.

The first four problems listed (i, ii, iii, iv) could be solved by removing the Polygeyser from the system. Replacing the Polygeyser with a Moving Bed Bio-Reactor on a side loop would aid in mainline pumping reliability, improve nitrification efficiency, simplify some of the water replenishment logistics, and improve temperature regulation. Every agitation event of the Polygeyser resulted in a brief period of no water flow to the culture tanks. If agitation events were too infrequent, the filter became fouled, resulting in a reduced flow to the culture tanks. By removing the Polygeyser, culture tanks would have continuous unobstructed water flow. Because of the large amount of water displaced by the Polygeyser during air-assisted backwashes, water temperatures fluctuated. Replacing the Polygeyser with a Moving Bed Bio-Reactor would improve water temperature control. To achieve targeted nitrification rates, a moving bed bioreactor with 1.5m^3 media capacity could be placed on a side loop. Additionally, the air compressor, booster pump, sump pump, and IBC tote water reservoirs associated with Polygeyser could all be eliminated. Replenishment water could be supplied directly from the dechlorinator. Removing all these components would reduce electrical demand, increase floorspace, and eliminate many potential failure points.[54]

The problem of inadequate reserve water pumping (v) could be solved with the installation of a 0.85m^3 minimum-capacity collection sump installed downstream from the drum filter to provide a larger water reservoir for pumping. Total water reserve would then increase from approximately 1.5minutes of main line pumping capacity to 2.5minutes of pumping capacity.[50] In the current design, after emptying a radial flow separator or discharging water from a single culture tank during routine cleaning, the system must replenish water to baseline levels before another tank or radial flow separator can be cleaned. If too much water is discharged too quickly from multiple radial flow separators or tanks, low water levels in the drum filter and degassing tower reservoir lead to air entrainment and pump cavitation.[55,56] While effective, the current design greatly extends the time required for daily cleaning and increases risk of pump damage during cleaning operations. Increased pumping reserve would allow cleaning operations to be completed in succession and reduce the risk of pump damage.

The lack of pumping flexibility and control (vi) could be alleviated by replacing the current fixed-speed main line pump with a variable

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speed pump to optimize energy consumption.[57,58] This would allow for flows to be easily-adjusted to align with fluctuations in biomass loadings during the production cycle.

The problem of undersized pipes for both treated water and drain lines (vii) could be easily solved by increasing pipe diameters. Larger diameters would accommodate higher flows. In addition, installing access points to all drain lines for periodic cleaning would greatly aid in minimizing the effects of biofouling and increase system reliability. Increasing pipe diameter for all pressure applications would also greatly reduce pipe friction loss and minimize potential pipe scouring.[50] Identification of fouling issues would be enhanced by adding flow meters, which would also increase control and awareness of system status. Increased control and awareness of pumping operations would increase energy efficiency, optimize flows throughout the system to match overall water quality design targets, and allow for remote monitoring capabilities should a system malfunction occur.

An emergency bypass must be added to direct water flow from the untreated section of the drum filter to the treated side (viii). In its current design, if a failure occurred, water cannot pass through the drum filter once the screen is obstructed, and water is discharged into the drain. When enough water is discharged, mainline pumping to the culture tanks is compromised.

The solution to mediocre occupational ergonomics (ix) is to increase the distances between the various components and provide clear access for tank cleaning and regular equipment maintenance.[59] With the configuration and spacing of this system, staff had to climb over pipes and squeeze into tight spaces for routine hatchery chores and maintenance. Ergonomic stress is the most common occupational safety and health claim for aquaculture workers in the United States,[60] making improving the occupational ergonomics of this system essential.

In conclusion, this first description of a Recirculating Aquaculture System for growing muskellunge is extremely important. Recirculating aquaculture is currently used to produce muskellunge for stocking into recreational fisheries,[10,12] but the systems are not described in detail. Recent research has indicated the need to grow muskellunge to the large sizes to maximize post-stocking survival,[61] and RAS is likely the only method available for this to occur efficiently and relatively-quickly.

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Conflicts of interest

We declare that there is no conflict of interest of any kind.

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