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Developments in recirculating systems for Arctic char culture in North America

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Abstract

Arctic char (*Salvelinus alpinus*) tolerate high-density culture conditions, have an excellent fillet yield, are amenable to niche marketing, and are suitable for production within super-intensive recirculating systems. Much of the North American production of Arctic char has been within recirculating systems, which can provide more optimum water temperatures for fish growth and can also overcome limitations created by a lack of high-quality water resources or strict pollution discharge limits. This paper describes some of the developments that have been made in recirculating systems used to produce Arctic char and examines several North American facilities that have used recirculating systems to produce Arctic char. This description includes several state-of-the-art recirculating systems that are now being used to commercially produce Arctic char and another that has just been built and is about to come on-line. This paper also describes several areas where advances have been made in cold-water recirculating system design in order to improve the water quality that they maintain at high feed loadings and to increase the production capacity of these systems. Several critical process improvements include: increased hydraulic exchange rates through the culture tank, superior culture tank designs, better oxygen control strategies and ozonation, improved design of forced-ventilated cascade aeration columns, full flow drum filtration, and better pipe and sump cleanout designs. Several of the strengths and weaknesses of Arctic char production within land-based recirculating systems are also discussed.

Keywords: Recirculating; Reuse; Arctic char; Aquaculture; Fish farming

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1. Introduction

To achieve success as a commercial business, an intensive fish farm must typically avoid failure in every aspects of business management, marketing, fish husbandry, biosecurity, and culture system design. Engineers work during the design of an intensive aquaculture system to avoid design flaws within the water treatment components that would create water quality and/or fish health problems that could, in due course, preclude or reduce the success of the commercial fish farm. For example, engineers work to ensure that fish culture units are supplied with adequate mass and concentration of dissolved oxygen to meet the carrying capacity[1] requirements of the farm. In addition, they also design treatment units to remove waste metabolites—ammonia, carbon dioxide, and total suspended solids (TSS)—to prevent their accumulation to unsafe levels within recirculating systems. A failure in any of the treatment unit processes or in the oxygen supply to the culture tank that reduced the carrying capacity of the recirculating system would create serious water quality problems and could ultimately cause the fish farm to fail.

To achieve success as a commercial business, intensive aquaculture facilities should also provide biosecurity (to reduce the likelihood of fish pathogen introduction) and produce a fish species that can provide a positive return on investment due to a combination of factors, such as: a relatively high market price, respectable growth rates, good feed conversion rates, tolerance to high culture densities, and comparatively high fillet yields.

Arctic char (*Salvelinus alpinus*) is a unique aquaculture species that exhibits several advantages for land-based systems, such as:

1. Arctic char can demand a relatively high wholesale price because it is still perceived as a high value species due to its limited supply and uniqueness of product (Delabbio, 1995).
2. Arctic char has good flesh taste and texture (Kim, 1993; Aarset, 1999).
3. Arctic char produce an excellent fillet yield that is approximately 7–8% higher than a rainbow trout's fillet yield due to the Arctic char's relatively broad body shape and small head (Glandfield, 1993).
4. As other salmonids, Arctic char can produce feed conversion rates close to 1:1.
5. Arctic char thrive at high densities and tolerate culture densities of up to 120 kg/m^3 (Jorgensen et al., 1993).
6. Arctic char can survive short-term exposure to low dissolved oxygen concentrations (Delabbio, 1995).
7. Arctic char are more cold-water tolerant than many other trout and salmon and exhibit maximum growth at temperatures of 12–15 °C (Delabbio, 1995; Larsson and Berglund, 1998). In addition, unpublished research from Iceland indicates that the optimum temperature for grow-out of Arctic char may be closer to 10 °C (Thorarensen, Agricultural College of Holar, Iceland, personal communication).
8. Arctic char production in ocean pens has been limited due to seawater intolerance at low temperatures (Aarset, 1999), which may limit the market competition for Arctic char produced in land-based systems.

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[1] Carrying capacity simply denotes the maximum fish biomass that can be supported at a selected feeding rate.

9. Certain strains of Arctic char and their hybrids can grow comparable to Kamloop rainbow trout to a size approaching 1 kg (Bebak-Williams, 2001).
10. Arctic char seedstock can now be purchased twice annually from at least one North American supplier. Arctic char seedstock are available that have been tested and certified free from specific listed salmonid pathogens, which improves biosecurity.
11. Arctic char can maintain excellent fin condition at densities in excess of 100 kg/m^3 (Freshwater Institute, unpublished data), possibly because Arctic char do not feed as aggressively as rainbow trout.

Arctic char culture also faces several challenges:

1. Arctic char eggs and fry are relatively expensive and are only available from a limited number of suppliers, mostly located in Canada, Iceland, and Norway.
2. Broodstock development is just beginning in North America.
3. Early sexual maturation of char can reduce growth rate and flesh quality before the fish have reached market size.
4. Arctic char do not feed as aggressively as rainbow trout. Therefore, feed must be broadcast across the culture tank at relatively slow application rates and during multiple feeding events each day in order to effectively feed Arctic char (Linnér and Brännäs, 2001).
5. With respect to susceptibility to common salmonid bacterial pathogens, Freshwater Institute research (Bebak-Williams, 2001) found that Nauyuk and Labrador Arctic char strains are similar and were either the most sensitive host or they were comparable in sensitivety to rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*). Both char strains were highly susceptible to *Yersinia ruckeri*, similar to rainbow trout. Host responses were similar for challenges with *Renibacterium salmoninarum* and *Aeromonas salmonicida*. Nauyuk and Labrador char were highly susceptible to both pathogens and were similar to brook trout while rainbow trout were very resistant.
6. Arctic char is an unknown in many markets. Also, rainbow trout and salmon are relatively low cost competition for Arctic char, so Arctic char must be marketed as distinguishably different and better to achieve premium prices.
7. Arctic char can develop excessive levels of visceral fat when fed moderately high energy diets.
8. Pigmentation of Arctic char flesh for marketability reasons is still debated, but most food-size Arctic char are fed pigmented feeds before they are harvested.

Much of the North American production of Arctic char has been within recirculating systems. Cold-water recirculating systems have undergone significant improvements within the last decade. Yet, there have still been a number of failed commercial Arctic char farms. This paper reviews some of the reasons—from an engineering standpoint—that certain recirculating facilities producing Arctic char have succeeded (to date) or failed. Several specific North American facilities that have used recirculating systems to produce Arctic char (Table 1) are discussed. Most of these facilities are research and demonstration projects, i.e., Daniel's Harbour Arctic Char Project in Newfoundland, the Conservation Fund Freshwater Institute's char research systems in West Virginia, and the forthcoming Millbrook First Nation Band's Demonstration Char Farm in Nova Scotia. Two commercial fish farms (i.e., West Virginia Aqua LLC and Glacier Springs Fish Farms Inc. in Manitoba) and a

Table 1
Type of systems (e.g., single-pass, partial-reuse, fully-recirculating) used for hatching, fry and fingerling culture, and grow-out of food-size Arctic char used at the facilities involved in this evaluation

Facility	Hatching system	Fry system	Fingerling system	Grow-out system
Daniels' Harbour	One single-pass system receiving 5 °C well water	One single-pass system receiving heated (≤12 °C) well water	Same system as fry system	One fully-recirculating system receiving fry system (≤12 °C) water
Freshwater Institute	One chilled recirculating system (6–12 °C)	One single-pass system receiving (12.5 °C) spring water	One partial-reuse system receiving (12.5 °C) spring water	One fully-recirculating system receiving (12.5 °C) spring water
MCRA Hatchery	One chilled recirculating system (6–15 °C)	One single-pass system receiving (14.5 °C) mine water	One partial-reuse system receiving (14.5 °C) fry system water	None
West Virginia Aqua	None	None	None	Three fully-recirculating system receiving (14.5 °C) mine water
Glacier Springs	One single-pass system receiving 5 °C well water	One fully-recirculating system receiving (6–8 °C) well water	Same system as fry system	Planned for future expansion
Millbrook First Nation	None	None	None	Two fully-recirculating system receiving (8–10 °C) well water

nonprofit hatchery (i.e., the Mingo County Redevelopment Authority Hatchery in West Virginia) are also discussed. Finally, general conclusions are made on recirculating systems designs for Arctic char production and opportunities and challenges for these ventures.

2. Daniel's Harbour Arctic Char Project (Newfoundland, Canada)

2.1. Background

In 1991, the Great Northern Peninsula Development Corporation initiated a pilot project to ascertain the economic and biological viability of culturing Arctic char in the Daniel's Harbour area of the Northern Peninsula of Newfoundland (Wilton, 2001). The Daniel's Harbour Project was mandated to assess the growth potential of Arctic char, and if warranted, define an appropriate strategy to develop char culture in the region. This project ran from 1991 through 1995 and completed a series of evaluations on the growth performance, hatching/early rearing success, and preliminary strain comparisons of Arctic char. The results from these assessments indicated that the establishment of a pre-commercial production facility at Daniel's Harbour was justified to provide a means of assessing both technical and economic potential of char culture in Newfoundland. Approval for the development of a land-based Arctic char production unit on the existing hatchery site in

Daniel's Harbour was received in June 1996 from the Canada/Newfoundland Cooperation Agreement on Strategic Regional Diversification. Construction of the first phase of the new facility—which had a production target of 50 mt per year of market size fish (1.0 kg)—was begun on 6 October 1997 and was completed by May 1998. The second phase of the project was never implemented, but would have doubled the production capacity of the Daniel's Harbour facility (Wilton, 2001). The physical layout and the general design parameters of the recirculating systems at the Daniel's Harbour Arctic Char Project are outlined below and have been summarized in Tables 1 and 2.

2.2. *Facilities and recirculating systems*

Two buildings were constructed. The main building—a wood frame structure with a metal siding exterior with measurements of 22 m × 12 m—housed an office, workshop/feed storage area, laboratory, lunchroom, and washroom on the front (northern) end. The main building also contained the hatching/early rearing area, electrical control and boiler room, and the back-up diesel generator. A double-plastic covered greenhouse (50 m × 12 m) attached at the southern end of the main building contained all of the recirculation equipment along with the production/grow-out tanks.

Egg incubation consisted of 128 vertically stacked trays that can hold more than 1.2 million Arctic char eggs. The incubation units were supplied with ambient ground water at a constant 5.0 °C. The early rearing area contains 12 circular combi tanks (1.5 m × 1.0 m deep) and four circular tanks (2.0 m × 1.0 m deep) for first feeding and fry/fingerling development. All early rearing tanks were supplied with single pass, heated water, at a maximum temperature of 12.0 °C. The two wells on the station were capable of supplying over 5000 l/min of ground water. Heated water discharged from the early rearing tanks was passed through a small swirl separator to remove particulate matter before the water was passed to the tank field (greenhouse) sump for recirculation through the grow-out tanks (Fig. 1).

Ambient ground water temperatures at Daniel's Harbour are a constant 5.0 °C. Therefore, providing temperatures of 10–14 °C to grow-out Arctic char in a single-pass system would require heating more water than was thought to be cost effective. For this reason a water recirculating system was installed for Arctic char grow-out. The recirculating system contained 12 circular culture tanks (5 m diameter and 2 m deep), with a total usable rearing volume of approximately 424 m^3 (Table 2). Each culture tank was equipped with three central stand pipes. The center standpipe (inverted) drew water and solids (faeces, feed, etc.) off the bottom of the fish tanks for delivery to the swirl separator (Fig. 1). A second pipe located near the centre, drew water from the surface and delivered it directly to the pump chamber in the sump (Fig. 1). The third pipe was used to drain the tanks to the outside settlement pond.

A cement sump with a usable water storage volume of 43.6–54.5 m^3 (about 1.5 times the volume of a single culture tank), served as reserve water capacity for filling tanks, houses the pump chamber, and contains tube settlers to facilitate solids removal. Water was pumped from the pump chamber into two fluidized-sand biofilters by two 1893 l/min submersible sump-pumps (Fig. 1).

The two fluidized-sand biofilters, each measuring 1.83 m diameter and 4.42 m high, were located in the tank field. Water was pumped from the sump to a false-floor chamber located

Table 2
A comparison of the Arctic char recirculating systems

Facility	System	No. of recirculating or reuse modules	No. of culture tanks per module and volume of each culture tank (m^3 tanks)	Culture tank exchange (minutes)	Total flow per module(l/min)	Biofiltration, no/yes (and type)	Ratio of reused water flow (%)	Typical mean TAN/NO_2-N, concentrations (mg/l)	Typical mean CO_2 concentration (mg/l)	Solids removal units and their placement	Ozone/UV irradiation use, no/yes and comments
Daniels' Harbour	Grow-out system	1	12 × 35	112	3790	Yes, FSB	94–95	$\leq 1.0/\leq 0.2$	30–50	Swirl separator and drum filter treat bottom drain flow; no treatment on elevated drain flow except the settle-deck used in pump sump	No O_3 or UV units
Freshwater Institute	Fingerling system	1	3 × 10	15–24	1200–1850	No	85–88	$\leq 1.7/\leq 0.2$	≤ 20	Bottom drain flow is discharged from partial-reuse system; drum filter treats elevated drain flow before it is recirculated	No O_3 or UV units
Freshwater Institute	Grow-out system	1	1 × 150	31	4800	Yes, FSB	93–96	$\leq 1.0/\leq 0.3$	≤ 22	Bottom drain flow is treated by a swirl separator and a drum filter while the elevated side-wall drain flow passes through the same drum filter before it is recirculated	O_3 occasionally, UV yes

MCRA Hatchery	Fingerling system	1	4 × 10, 4 × 150	≤15	1900–3000	No	∼50	≤1.2/≤0.1	≤18	Single-drain tanks discharge to a drum filter before water is reused	No O_3 or UV units
West Virginia Aqua	Grow-out system	3	4 × 40, 1 × 140	27	11300	Yes, FSB	93–99	≤0.5/0.1	≤18	Bottom drain flow is discharged from recirculating system; elevated flow passes through drum filter before reuse	O_3 yes, UV no
Glacier Springs	Nursery system	1	70 × 2.3	40	4800	Yes, FSB	∼95	na/na	na	Single-drain tanks discharge to a drum filter before water is recirculated	No O_3, UV yes
Millbrook First Nation	Grow-out system	2	2 × 36, 2 × 118, 1 × 176	45	10500	Yes, polystyrene bead biofilter	99.7	na/na	na	Bottom drain flow is treated by a swirl separator and a drum filter while the elevated side-wall drain flow passes through the same drum filter before it is recirculated	O_3 yes, UV no

FSB: fluidized-sand biofilter.

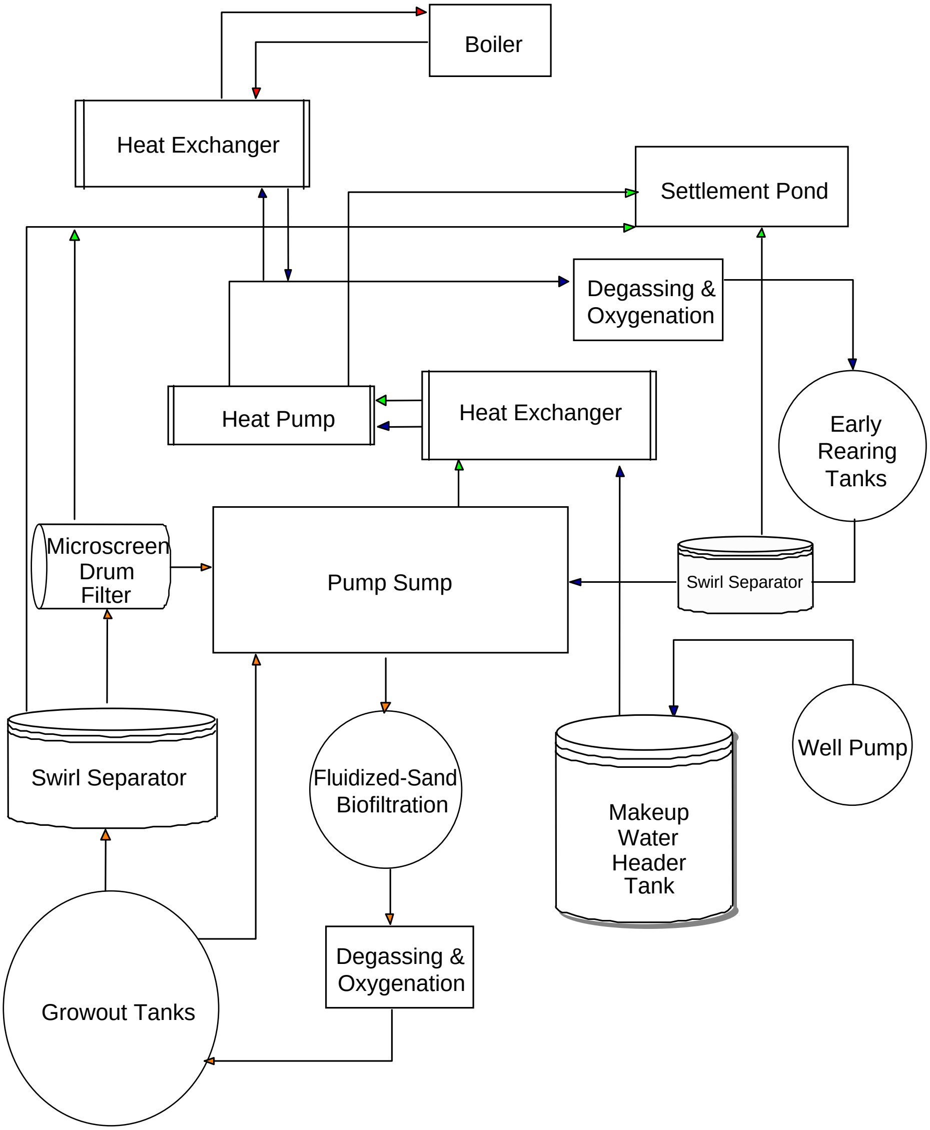

Fig. 1. Process flow drawing of make-up water pretreatment and water recirculation processes used at the Daniel's Harbour Arctic Char Project.

in the bottom of the biofilters, which uses a perforated plate to distribute the water flow uniformly under the sand bed. Water would rise up through the sand bed to the top of each biofilter at a superficial velocity of approximately 1.2 cm/s. Ammonia and nitrite were removed from the water as it passed through the fluidized-sand biofilter. After exiting the top of each biofilter, the water flowed through a trough to the aeration system (Fig. 1).

Water leaving each biofilter first cascaded through a degassing unit (Fig. 1) that provided a 1 m drop over eight perforated plates (cascading column) and an Enka-type (forced air) aerator to strip dissolved carbon dioxide from the water. The water then flowed by gravity through a low head oxygenation (LHO) unit where purified oxygen gas was supplied to supersaturate the flow with dissolved oxygen before the water flowed by gravity to the 12 culture tanks (Fig. 1).

The swirl separator was designed to remove the larger/heavier solids collected from the centre stand pipe in the rearing tanks. The heavier solids were concentrated at the bottom of the cone in the swirl separator and were drained from the system to a sludge holding tank and settlement pond by means of an external stand pipe. The water that was reused was drawn from the centre surface of the swirl separator and was piped to the microscreen drum filter (Fig. 1). After passing through the microscreen filter, the water flowed by gravity to the pump sump. The microscreen filter operated on a float switch system where the sludge collected on the sieve panels was automatically washed to the sludge holding tank and settlement pond.

2.3. Conclusions

From the start, the Daniel’s Harbour Arctic Char Facility was beset with numerous technical problems that had a significant negative impact on the life cycle of the char. The actual design of the facility did not meet certain requirements specified in the original proposal, which resulted in (1) unsatisfactory water quality—affecting fish health and growth rates, (2) poor water temperature control, which slowed fish growth (and annual fish production) and limited broodstock holding capability and on site egg production, and (3) a reduction in the overall carrying capacity of the facility, which negated the ability to produce economic quantities of market size char. The main factors that limited the production capacity of the operation were oxygen delivery, solids removal, and carbon dioxide management (Wilton, 2001). The ability to maintain safe dissolved oxygen and carbon dioxide levels at stocking densities in excess of 40 kg/m^3 was increasingly difficult due to the relatively low hydraulic exchange through the culture tanks, which were exchanged approximately once every 112 min at maximum flow (Table 2). In hind sight, the authors would rather that the recirculating system had been designed to exchange the culture tank water volume at least once every 30–45 min, which would have more than doubled the amount of dissolved oxygen that could be supplied to the fish.

Furthermore, the solids removal system also proved to be inadequate and water quality was severely compromised. Three problems with solids control rapidly became apparent: (1) the dual drains in the centre of the culture tank did not fractionate solids to the bottom drain as effectively as desired; (2) the bulk of the water discharged from the culture tank through the elevated drain was not passed through a microscreen drum filter; (3) solids accumulating in the settle-deck sump were mineralizing within the recirculating system and removing the accumulated biosolids from these sumps was difficult. This deterioration in water quality likely affected the growth of the char and exerted a large oxygen demand on the system. Consequently, as the biomass increased, the staff was spending a disproportionate amount of time and energy managing the system, relative to their fish husbandry duties.

After an extensive review of the Daniel's Harbour Arctic Char Facility (Wilton, 2001), it was evident that the recirculating system was designed on principles and technologies that have been used in salmon smolt hatcheries in Atlantic Canada and Maine (USA). However, these salmon smolt farms often operate in batch production mode—where the system could be emptied and cleaned once to twice annually—and this design apparently could not accommodate the demands of Arctic char that were to be reared at the proposed densities of $\geq$100 kg/m^3 (Wilton, 2001).

While this venture did not meet the criteria of firmly establishing economic feasibility, it also did not imply that Arctic char culture in a properly designed recirculation facility would not have merit. Indeed, the fact that the Arctic char held in such poor conditions at the Daniel's Harbour operation almost reached production targets is a testament to the tenacity of the species (Wilton, 2001).

3. Freshwater Institute Char Research Facility (West Virginia, USA)

3.1. Background

Since 1996, the Conservation Fund Freshwater Institute (CFFI) has been investigating the potential of Arctic char culture in the Appalachian region of the United States. In parallel research conducted since 1989, the CFFI has been working to develop recirculating systems and technologies for large-scale cold-water fish production. These projects have been supported at the CFFI through grants from the US Department of Agriculture Agricultural Research Service (USDA-ARS). A primary thrust of the more recent research has been to develop technology and assess food-fish production within a one-tenth scale commercial model with an annual production target of 45 mt (100,000 lb).

Arctic char have been cultured in the CFFI's recirculating systems since 1999. Certified pathogen free (Title 50) eyed eggs are imported twice annually and these eggs are hatched at 6 °C in a chilled recirculating system (not discussed here). When the fry have hatched they are transferred to 1.2 m (4 ft) diameter fry tanks in flow-through conditions. The char are grown in the flow-through system (at 12–13 °C) until they reach about 15–20 g, at which point they are transferred into a partial-reuse system used for culture of advanced fingerlings. The char fingerling are reared in the partial-reuse system (discussed below) until they reach about 150–200 g, at which point the fish are transferred to a fully-recirculating system (discussed below) for grow-out to about 1.3 kg (Table 2). Automatic feeders feed a high-energy commercial salmon or trout growers diet (between 40 and 46% protein and 16–19% fat) to char in the fingerling and grow-out systems.

3.2. Partial-recirculating nursery system

The Freshwater Institute's pilot-scale partial-reuse system (Fig. 2) consists of three 3.7 m (12 ft) i.d. by 1.1 m (3.5 ft) deep circular 'Cornell-type' dual-drain culture tanks and operates at a total system flow of 1200–1850 l/min to exchange the culture tank volume every 15–24 min (Summerfelt et al., 2000a). The water flowing from the culture tank's bottom-center drain is immediately discharged from the partial-reuse system. The water

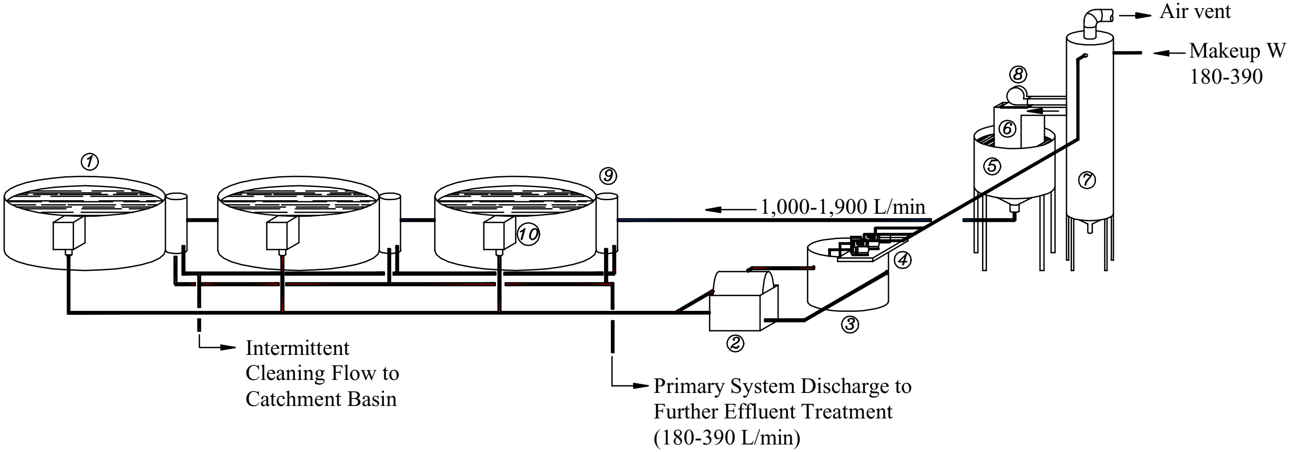

Fig. 2. The partial-recirculating system at the CFFI serves as a nursery to grow Arctic char fingerlings from 15 to over 150 g (from Summerfelt et al., 2000a). The units are defined according to the following: (1) 3.7 m $\phi \times 1.1$ m culture tank; (2) microscreen drum filter; (3) 1.8 m $\phi \times 1.2$ m pump sump; (4) three 1.5 hp reuse pumps; (5) header tank (with cone bottom to improve cleaning); (6) LHO; (7) carbon dioxide stipping column (with cone bottom to improve cleaning); (8) low-head and high-volume fan; (9) triple standpipe sump (to direct bottom flow and observation of waste feed); (10) "Cornell-type" side-wall drain. The CAD drafting was provided by PRAqua Technologies Ltd. (Nanaimo, BC).

flowing out of the ‘Cornell-type’ side-wall drains is collected and filtered through 90-μm sieve panels within a rotating drum filter before it enters a pump sump (Fig. 2). Other than a small water overflow from the pump sump, the majority of water is pumped by one, two, or three 1.5 hp centrifugal pumps against approximately 0.4 bar (6 psig) pressure to the top of a ventilated aeration column (Fig. 2). The water discharged from the aeration column then gravity flows back to the culture tanks after first passing through a low head oxygenator (LHO). The LHO was installed within a cone-bottom sump (Figs. 2 and 3) to simplify periodic removal of settled solids. No biofilter is used in the partial-recirculating system and total ammonia nitrogen (TAN) accumulation is controlled at less than 1.7 mg/l by dilution with 237–357 l/min of fresh make-up water and by pH control of the stripping fan to minimize the fraction of unionized ammonia present (Summerfelt et al., 2000a). The pH set-point is determined by the alkalinity of the make-up water (among other factors) using a nomographic technique described elsewhere (Summerfelt et al., 2001). Water temperature in the

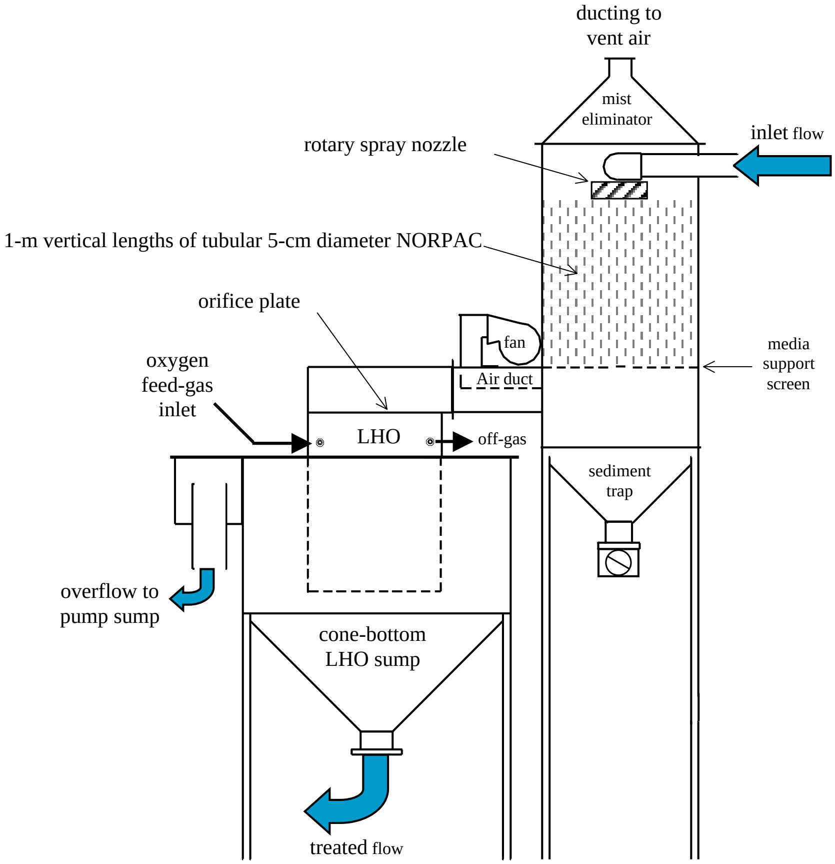

Fig. 3. The design and placement of a LHO unit and a stripping column within the CFFI’s partial-reuse system (from Summerfelt et al., 2000a) illustrates how cone bottom sumps can be incorporated in recirculating systems to allow for simple and rapid flushing of sediment and biosolid accumulations from sumps.

partial-reuse system is within 1 °C of the make-up water temperature, i.e., 12.5–13.5 °C. The partial-reuse system has supported a maximum of 68 kg feed per day over a period of several weeks. However, the partial-reuse system maintains dissolved oxygen, carbon dioxide, and unionized ammonia concentrations within safe limits at the 45–50 kg feed loading rate and this feed loading is a more realistic maximum feed loading rate on this system.

The 'Cornell-type' dual-drain tank rapidly and gently concentrates and flushes about 80% of the total suspended solids produced daily through the tank's bottom-center drain (Summerfelt et al., 2000a). This discharge leaving the system amounted to 12–15% of the tank's total water flow, but this flow flushed the majority of particles from the system within 1–2 min of their deposition into the culture tank (Summerfelt et al., 2000a). Solids fractionation within the 'Cornell-type' culture tanks was extremely effective. At high fish loading levels, the total suspended solids concentration discharged through the three culture tanks' bottom-center drains was roughly ten times greater than the total suspended solids concentration that discharges through the three culture tanks' side-wall drains, which averages 1.5–2.5 mg/l (Summerfelt et al., 2000a).

3.3. *Fully-recirculating grow-out system*

A fully-recirculating system is currently being used for Arctic char grow-out (Figs. 4 and 5). This recirculating system uses two 5 hp pumps to recirculate 4800 l/min (1250 gal/min) of water (Summerfelt et al., 2003). The water is pumped at a pressure of 0.56 bar (8.3 psig) through a 2.7 m (9 ft) diameter × 6.1 m (20 ft) tall Cyclo Bio^{TM} fluidized-sand biofilter (Figs. 4 and 5). The water flow exits the top of the fluidized-sand biofilter and flows by gravity through a cascade stripping column, a low head oxygenation unit, and a UV irradiation unit before being piped to a 150 m^3 (40,000 gal) culture tank (Figs. 4 and 5). The cascade stripping column and low head oxygenation unit have been described elsewhere (Summerfelt et al., 2003). The recirculating water flow exchanges the culture tank volume approximately once every 30 min. About 93% of the water exits the culture tank through its 'Cornell-type' side-wall drain and is directed through a microscreen drum filter before returning to the pump sump (Figs. 4 and 5). About 7% of the water exits the culture tank through its bottom drain and is then directed to a swirl separator (Figs. 4 and 5). Water treated by the swirl separator is split and some is discharged while the remaining flow is recombined with the water flowing to the microscreen drum filter, depending upon the system exchange rate desired. The recirculating system operates with about one to two complete system turnovers per day to prevent water temperature from exceeding 14.5 °C. A mort trap and mechanical mort flushing system are used to rapidly remove daily mortalities from the bottom of the culture tank (Figs. 4 and 6).

The fully-recirculating grow-out system was designed to adhere to principles of good biosecurity in that all parts of the system will be accessible for cleaning while on-line or off-line. The fully-recirculating system was designed using criteria found in Summerfelt (1996), and Summerfelt and Hochheimer (1997), Summerfelt et al. (2000a, 2001). Marine Biotech Inc. (Beverly, MA) completed the structural and mechanical design and then installed this recirculating system.

Beginning in March of 2001, four cohorts of 100–200 g Arctic char and one cohort of a hybrid, all female, brook trout × Arctic char were sequentially stocked into a single 150 m^3

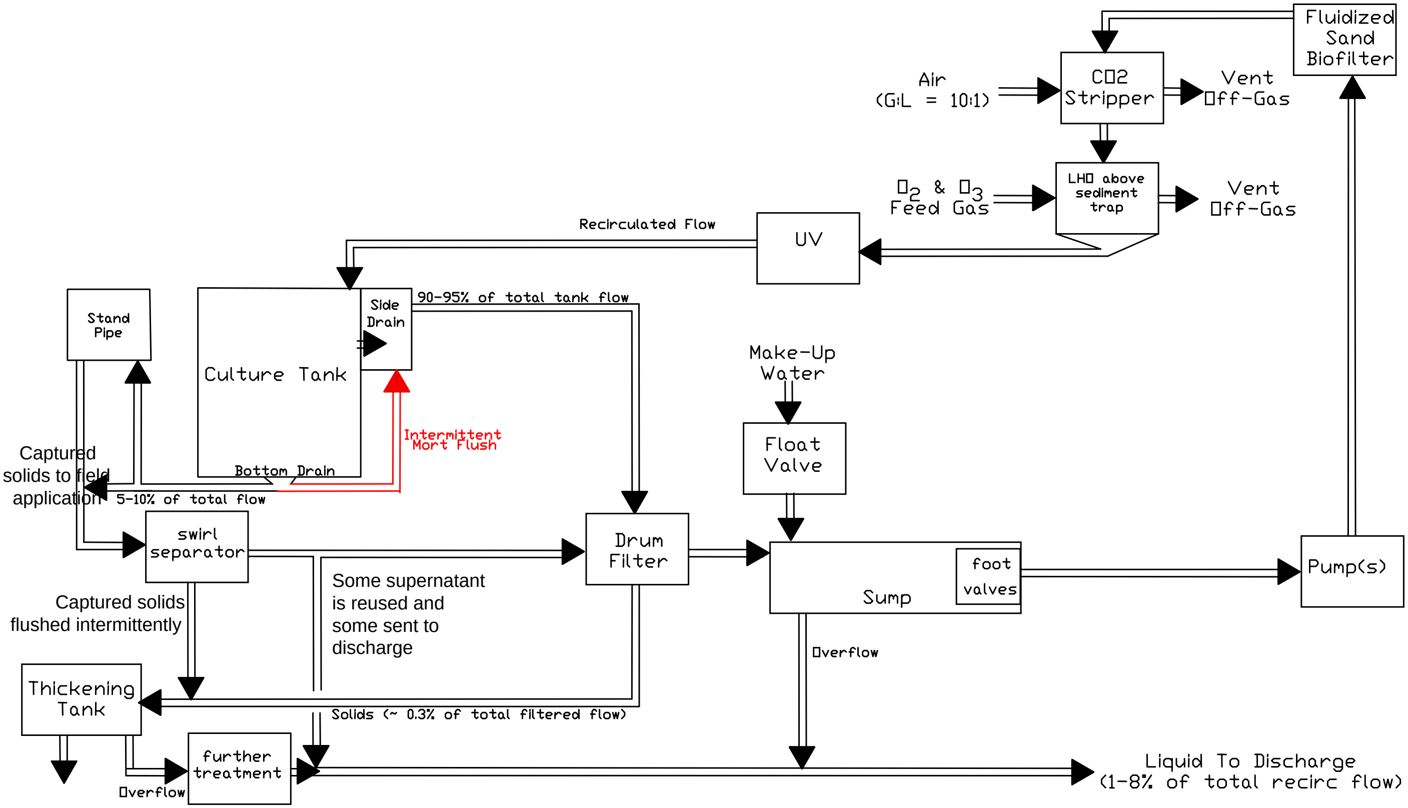

Fig. 4. A process flow drawing of the 4800 l/min fully-recirculating Arctic char grow-out system at the CFFI.

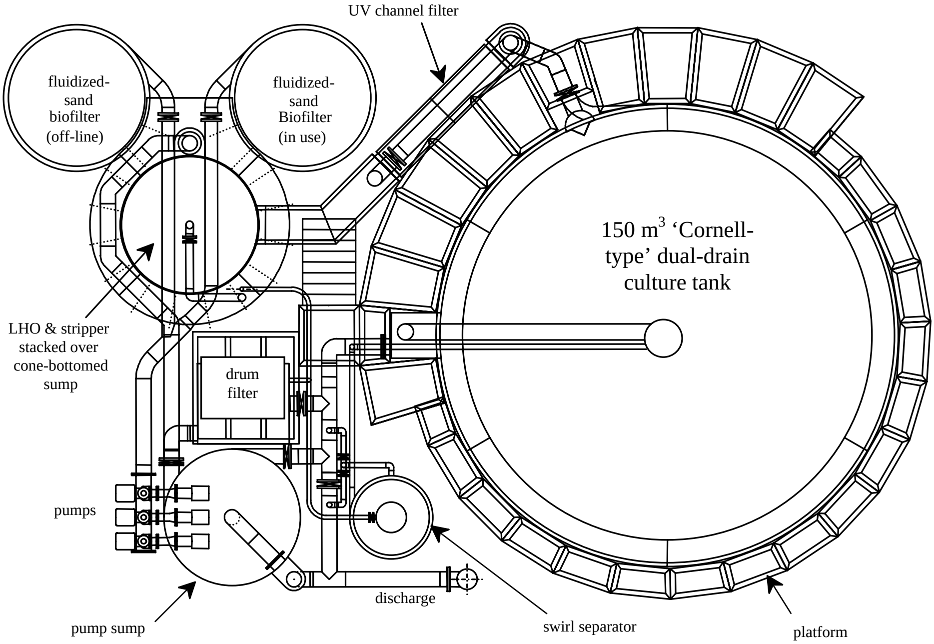

Fig. 5. The 4800 l/min fully-recirculating system at the CFFI. Drawing courtesy of Marine Biotech Inc. (Beverly, MA).

culture tank within the recirculating grow-out system. A new cohort of char was stocked approximately once every 6 months. A selective harvest strategy was used to sustain high biomass productivity under maximum production densities of 100–130 kg/m^3. During this period, technologies were evaluated for managing routine fish mortalities (e.g., using a

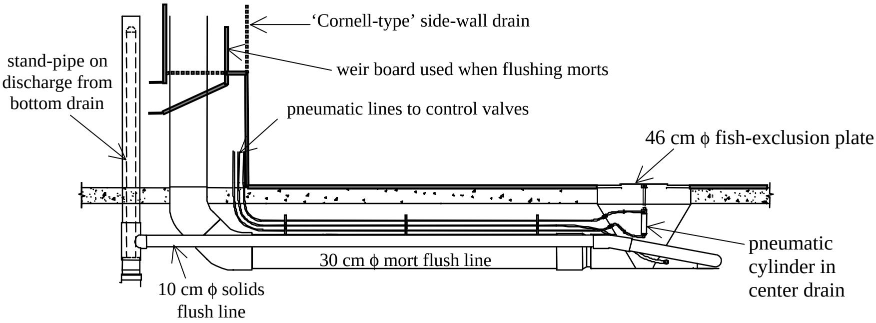

Fig. 6. A center drain sump incorporating a pneumatic cylinder allows an operator to raise an 46 cm (18 in.) diameter center plate to flush dead fish from the bottom of the culture tank when a 30 cm (12 in.) diameter stand pipe is pulled at the back of the tank's 'Cornell-type' side-wall drain box. The 30 cm diameter stand pipe is reinserted less than 0.5–1.0 min later, shutting off the flow through the 30 cm diameter mort flushing pipe. The center plate is then raised to close the tank's bottom-center drain. Dead fish are captured above an aluminum screen in the side-wall drain sump. The dead fish are removed and live fish caught in the side-wall sump can be returned to the culture tank.

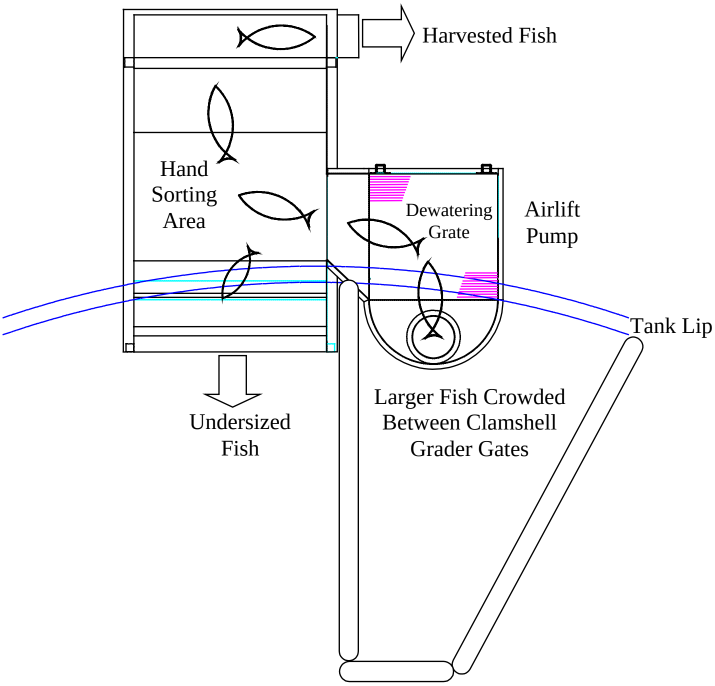

Fig. 7. The CFFI developed a portable and relatively low cost airlift fish pump (US$ 5000) that was used to remove fish from the circular tank to a sorting box, where they are hand sorted according to size and condition. The airlift fish pump/dewatering box was fabricated from aluminum and was relatively lightweight (47 kg), and compact (roughly width × length × depth, 200 cm × 160 cm × 41 cm), which made it easy for two people to set-up and move into position at the culture tank. The unit was placed above and to one side of the culture tank, resting on the tank's lip. The unit airlifted fish from the bottom of the culture tank, dewatered the fish, and returned the pumped flow back to the culture tank. Fish pumped from the culture tank were manually sorted within the integral hand-sorting box. Larger fish were hand swept to one end of the box (where they slid down a chute into a palletized fish hauling tote containing oxygenated water) while fish too small to harvest were swept to the other end of the box where they fell back into the culture tank on the backside of the crowder/grader clamshell. Once the palletized hauling tote was filled with fish, a forklift moved the hauling tote to the depuration tank where the harvested fish were held off-feed for an average of 14 days. Drawing courtesy of Fabritek Company Inc., Winchester, VA).

pneumatically actuated bottom drain cover; Fig. 6), size sorting fish during harvest (e.g., using a clam-shell grader and an airlift fish pump with a hand-sorting box, Fig. 7), and assessing fish size distribution using a passive submersible biomass scanner by VAKI DNG (Kópavogur, Iceland).

The fully-recirculating system maintained safe water quality for the Arctic char (Table 2). Water temperatures ranged from 13–15 °C. The fluidized-sand biofilter removed approximately 70–80% of the total ammonia nitrogen with each pass through the biofilter and maintained relatively low concentrations of nitrite. Thus, total ammonia nitrogen and nitrite nitrogen levels exiting the culture tank were maintained at approximately ≤0.4–1.0 and 0.05–0.3 mg/l, respectively (Table 2). The air ventilation rate through the cascade columns controlled the accumulation of dissolved carbon dioxide at concentrations ≤17–22 mg/l

(Table 2). Purified oxygen gas added in the LHO units produced dissolved oxygen concentrations entering the culture tank of 13–19 mg/l, which were adjusted according to the oxygen demand in the fish culture tank. Dissolved oxygen concentrations were maintained at 9–11 mg/l in the culture tank by adjusting the dissolved oxygen concentration carried into the tank and by the twice per hour hydraulic exchange rate through the culture tank. Solids fractionation between the 'Cornell-type' side-wall drain and the bottom-center drain was effective and the mean total suspended solids concentrations maintained in the culture tank water column was only 3–5 mg/l.

Recurring outbreaks of respiratory disease associated with a gram (−) intracellular bacteria with characteristics of chlamydial and/or rickettsial species occurred in the pure strain Arctic char cohorts, which at times caused mortality and limited growth (Bebak-Williams, 2001). However, the last cohort stocked was an all female diploid brook trout × Arctic char hybrid (e.g., 'brook-char' hybrid) from Alleghaneys Fish Farm Inc. (St. Philemon, Que., Canada) and this cohort appeared to resist the respiratory disease.

The fully-recirculating system was designed to support a maximum sustained feed loading in excess of 200 kg per day. However, some fish mortality and reduced feeding rates were caused by recurring outbreaks of respiratory disease (mentioned above) and due to slower growth among the first (and only) cohort of pure Nauyuk strain (i.e., Yukon Gold strain) Arctic char from Icy Waters (White Horse, Yukon, Canada) when they approached 1.0 kg in size. These reduced feeding rates, unfortunately, limited the total feed loading on the fully-recirculating system to approximately 120–150 kg per day during periods with maximum fish growth. The three cohorts of Nauyuk × Tree River Arctic char from Icy Waters and the single cohort (also the last cohort) of 'brook-char' hybrid were the fastest growing char produced at the CFFI. Most of the cohort of hybrid 'brook-char' had reached or exceeded harvest size ($\geq$1.3 kg) within 14–18 months post-hatch. However, the pure Nauyuk strain and the Nauyuk × Tree River strain Arctic char cohorts were all affected by recurring respiratory problems caused by the chlamydial and/or rickettsial organisms, which reduced their overall growth to the point that 16–32 months (post-hatch) were required for the majority of surviving fish in these cohorts to reach or exceed market size. A small percentage of the Nauyuk × Tree River strain (diploid) Arctic char grew much faster than the average fish in these cohorts and reached 3–4 kg during the same period. Unfortunately, except for the first cohort of pure Nauyuk strain and the last cohort of hybrid 'brook-char' (Fig. 8), mean cohort growth rates could not be tracked after the fish had been stocked into the grow-out tank due to the mixed cohort environment.

The feed conversion rates in the grow-out system were estimated at 1.2–1.3 kg feed required for each 1.0 kg of fish biomass.

Sexual maturation was also monitored. Except for a tiny fraction of precocious males, the cohorts of diploid Arctic char from Icy Waters International showed no or little gonad development even up to 2.5 years post-hatch. However, the all female 'brook-char' hybrid (diploids) showed some gonad development in approximately 20% of the population after 14–18 months post-hatch, i.e., when they were approaching or had reached harvest size (1.3 kg).

Approximately 40 mt (87,400 lb) of food-size Arctic char were harvested from the Freshwater Institute's recirculating grow-out system during the 1 year period that ended in late August 2003. The majority of fish (i.e., 30 mt at a 2.8 lb mean size) were donated to the

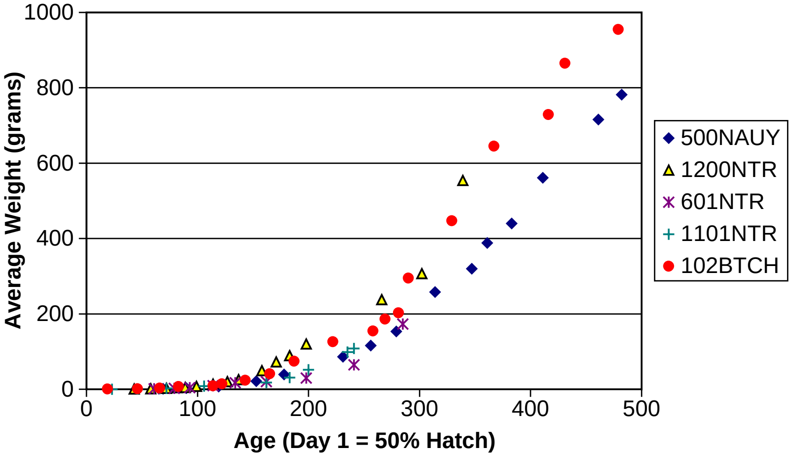

Fig. 8. Growth (average weight in grams) of the five cohorts of char cultured to food-size at the CFFI. Selective harvest of the largest brook trout × Arctic char hybrid occurred after their 400th day (post-hatch) and may have reduced the growth data collected beyond this age. ((◆) Nauyuk Arctic char hatched in June 2000; (△) Nauyuk × Tree River char hatched in December 2000; (✳) Nauyuk × Tree River char hatched in June 2001; (+) Nauyuk × Tree River char hatched in November 2001; (●) brook trout × Arctic char hybrid hatched in January 2002).

Virginia Food Banks Consortium—an America's Second Harvest program partner—while smaller donations were made to local Union Rescue Missions in Martinsburg, WV, Hagerstown, MD and Winchester, VA. The harvest sent to the Virginia Food Banks was commercially processed, producing a 'skin-on' fillet yield of 58 ± 1.3%.

3.4. Conclusions

The partial-reuse fingerling system and the fully-recirculating grow-out system both maintained excellent water quality under conditions with high sustained fish densities (e.g., 100–130 kg/m^3). Growth rates were excellent during periods when little or no respiratory infections were occurring. However, in order to challenge the two recirculating systems with higher feed loading rates and to work more closely with the new USDA Agricultural Research Service, National Center for Cool and Cold Water Aquaculture, all Arctic char were removed from the two systems in the spring and summer of 2003 and (after complete system disinfection) the two systems were stocked with an all female diploid Kamloop rainbow trout from Troutlodge Inc. (Sumner, WA). The two systems are a key component of a USDA-ARS funded project at the CFFI that is intended to create and evaluate functional, operational and economic efficiencies found through close design integration of the engineering of unit treatment processes, the criteria for biological performance of target culture species, and the requirements for product flow processes for farm production. However, beyond the research component, all systems were designed, installed, and operated to demonstrate the application of commercial-scale water reuse technologies and fish management systems in order to better transfer the experience gained to private and public producers. With the continued strong interest in recirculating aquaculture production systems, especially for cool and cold-water aquaculture production systems, the CFFI’s commercial-scale research system has provided a site for many visitors to see and get a feel for the complexity, technical skill, and scale of these types of fish farms. The CFFI’s facility is somewhat unique in that many commercial-scale or for-research systems are either not open to the public or they do not use technologies that are appropriate for a commercial-scale operation. Allowing visitors into a fish culture facility can threaten fish health by placing stress on the fish while leaning over the culture tank or by inadvertently transferring fish pathogens from the visitors to the fish culture water.

4. Mingo County Redevelopment Authority (West Virginia, USA)

4.1. Background

In 1994, with a grant from the Appalachian Regional Commission, the CFFI examined the economic feasibility of using discharge water from abandoned mines in West Virginia as inputs for aquaculture (Gempesaw et al., 1995). While some of the discharge is highly acidic or contains elevated levels of undesirable elements, such as aluminum or iron, billions of gallons (mostly in the southern portion of West Virginia) are clear, drinkable, pathogen-free, and cold enough to grow Arctic char. Even if only a fraction of the mine water suitable for aquaculture was utilized, then the new fish farms could generate substantial revenue and create hundreds of jobs in economically depressed parts of West Virginia.

In 1997, the Mingo County Redevelopment Authority (MCRA)—a non-profit corporation—received a USDA Rural Development grant that was used to subcontract with the CFFI to design a cold-water hatchery and provide on-going support to promote the development of cold-water aquaculture in Mingo County and help build the aquaculture technology infrastructure needed to boost the economy of southern West Virginia (Simmons et al., 2001). Construction of the MCRA Hatchery was completed in 2000 and the first cohort of Arctic char was imported from Icy Waters (White Horse, Yukon, Canada) in the spring of 2001 (Fig. 9).

4.2. Fish culture systems, water supply, and effluent treatment

The MCRA Hatchery is supplied with up to 3000 l/min (800 gal/min) of water pumped from an abandoned portion of an active coal mine (Fig. 9). The water is being pumped by the Mingo–Logan Coal Company to prevent water levels from flooding other active areas of the mine. The Mingo–Logan Coal Company has so far paid for the power to run these mine dewatering pumps and also installed the mine pumps and the piping to the MCRA Hatchery. The mine discharge water contains safe levels of iron, manganese, and aluminum. However, the water also contains 40–80 mg/l of dissolved carbon dioxide, a result of the water’s high alkalinity—about 400 mg/l as calcium carbonate. In addition, a severe dissolved nitrogen supersaturation problem could occur if the mine dewatering pump suctioned air into its pump intake along with the water. To prevent dangerous levels of dissolved gases from entering the hatchery, a counter-current cascade stripping column was designed in the top of a water-surge tank installed directly uphill from the hatchery building (Fig. 9). This

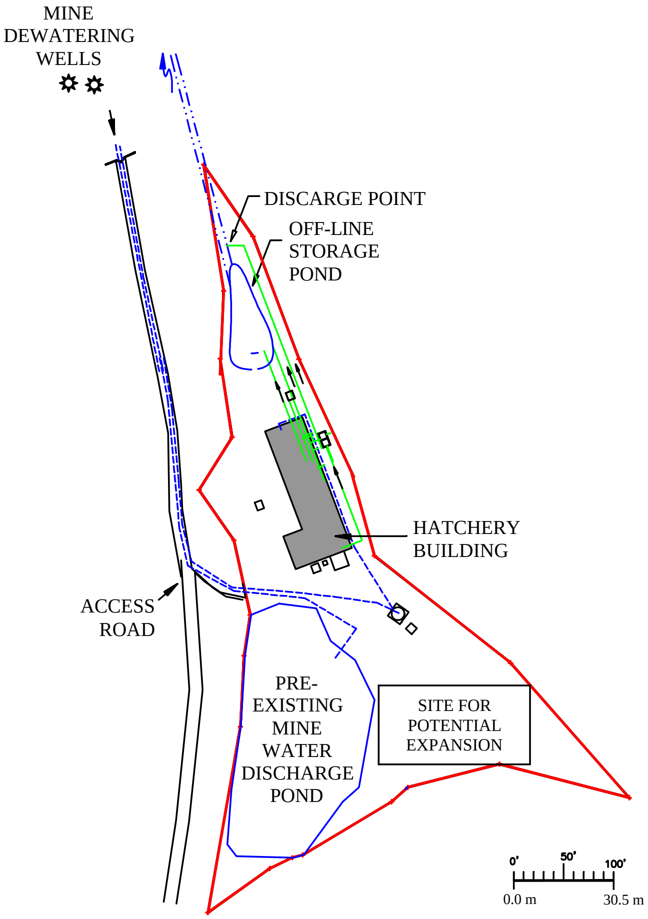

Fig. 9. A site plan of the MCRA Hatchery shows the location of the water storage tank and the pipes supplying both the water storage tank (from the mine dewatering pumps) and the hatchery building (Fig. 9).

stripping column/reservoir tank has successfully maintained the dissolved carbon dioxide at levels below 20 mg/l while also stripping some excess dissolved nitrogen saturation from the water supplied to the hatchery. Additionally, a non-pressurized oxygen column and a low head oxygenator were installed within the hatchery building (Fig. 10) to treat the water before it enters the fry and fingerling tanks, respectively. These columns are designed to drive out dissolved nitrogen to below saturation levels, while adding dissolved oxygen to levels 20–100% above saturation.

The mine discharge water temperature is about 14 °C. Therefore, MCRA Hatchery contains a chilled recirculating system for egg incubation (Fig. 11). However, Arctic char are raised in a single-pass system as fry and a partial-reuse system as fingerling (Fig. 10). Up to 1000 l/min of water are used in a single pass through twelve 1.8 m diameter by 0.6 m deep fry culture tanks after the flow has first been oxygenated within an non-pressurized packed

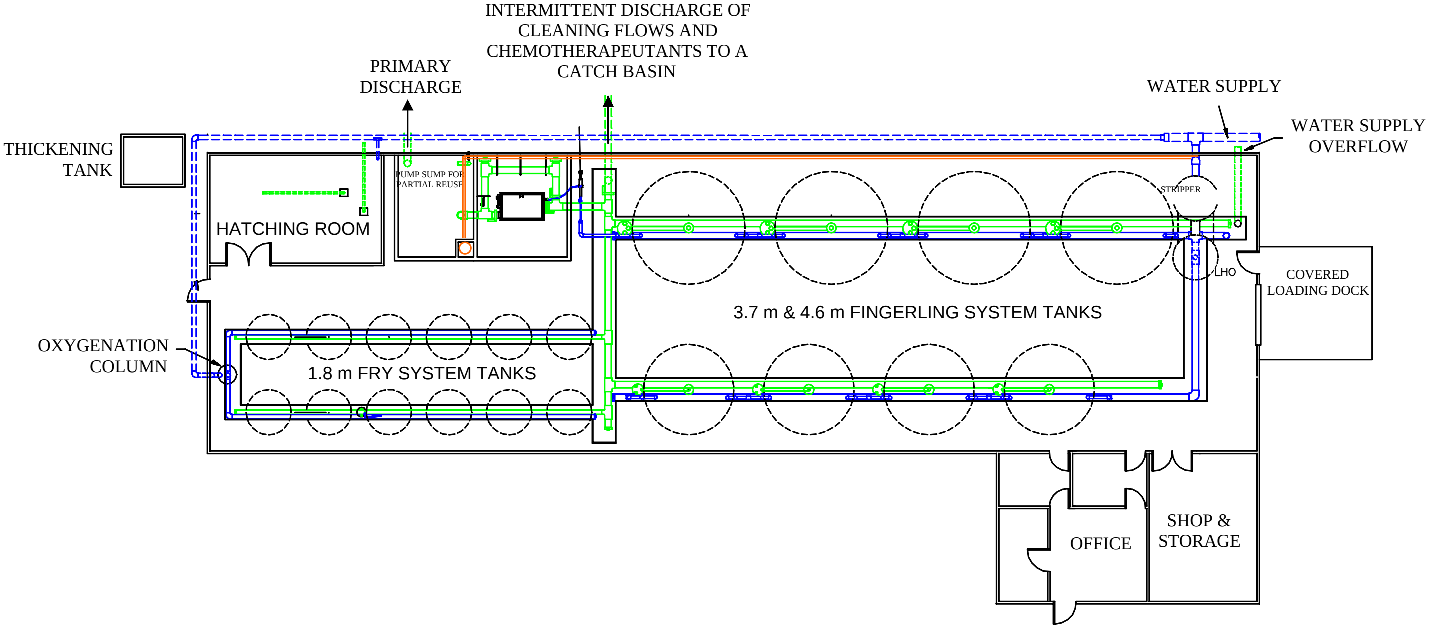

Fig. 10. The MCRA Hatchery building (12.2 m × 42.7 m [40 in. × 140 in.], excluding office and laboratory) contains separate systems for egg hatching, fry production, and fingerling production. Drawing courtesy of PRAqua Technologies (Nanaimo, BC, Canada).

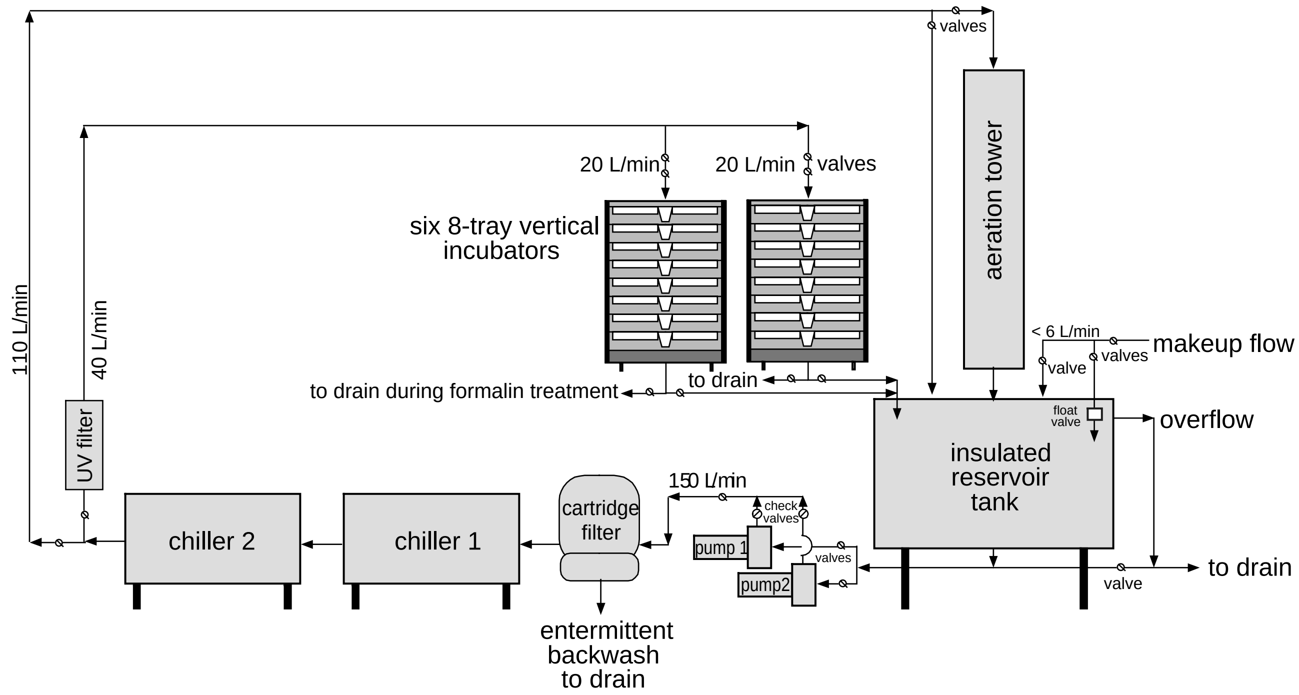

Fig. 11. A process flow diagram of the recirculating egg incubation system at the MCRA Hatchery. The system contains six 8-tray vertical incubators and the illustration is not to scale.

column. This water is then passed through the facilities common drum filter and is available for partial-reuse within the fingerling tanks. The fingerling system contains four tanks that are 3.6 m (12 ft) diameter by 1.1 m (3.5 ft) deep and four tanks that are 4.6 m (15 ft) diameter by 1.1 m deep (Fig. 10). The fingerling tanks are supplied with some 1900–3000 l/min (500–800 gal/min) of make-up water and/or recirculated water that is all pretreated at the head of the culture tanks through a ventilated cascade column followed by a LHO unit (Fig. 12). This water flow flushes the fingerling tanks at least once every 15 min.

The hatchery's effluent is treated through a microscreen drum filter before it is discharged. However, flows containing cleaning chemicals or chemotherapeutants are kept separate from

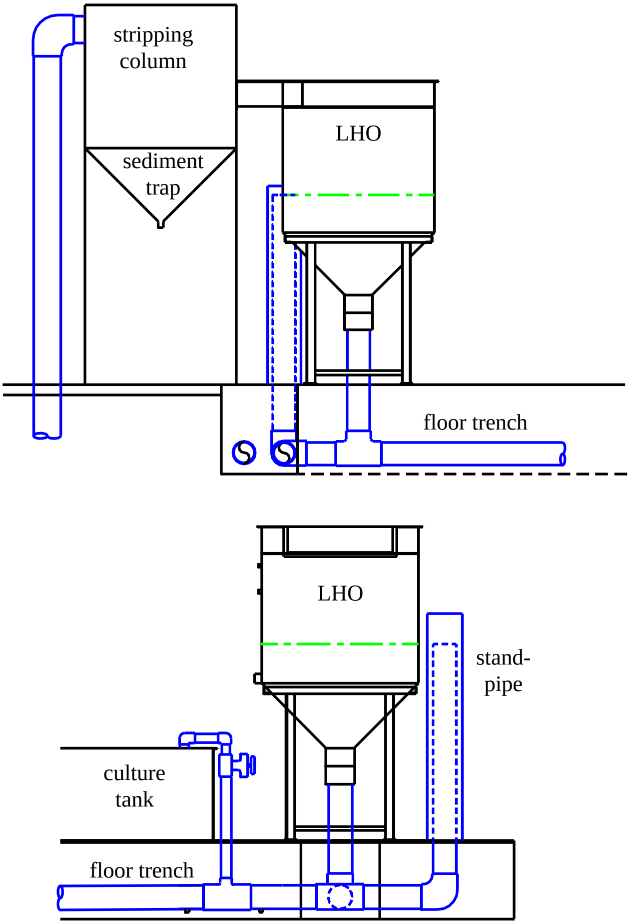

Fig. 12. Approximately 1900–3000 l/min (500–800 gal/min) of make-up and reuse water supplied to the fingerling system is first treated across a stripping column (to reduce dissolved carbon dioxide levels) and across a LHO (to produce dissolved oxygen supersaturation). Adjacent to the LHO, a standpipe sets the maximum water level in the LHO and provides an overflow to the floor trench. Drawing courtesy of PRAqua Technologies (Nanaimo, BC, Canada).

the hatchery's primary discharge by directing these occasional chemical-containing flows into floor trenches that run beneath all culture tanks (Figs. 10 and 12) and then to an off-line catchment pond (Fig. 9). The off-line catchment pond provides storage time for chemical degradation and keeps the chemicals separate from the discharge.

The waste collected on the microscreen drum filter, consisting of fish manure and waste fish feed, is automatically backwashed from the sieve panels. These biosolids are captured within a storage tank located outside the hatchery building (Fig. 9).

The fish production systems at the MCRA Hatchery have performed well and have been able to maintain excellent water quality under high fish loading levels (Table 2). With two egg shipments per year, as soon as one group of fish is transferred into the eight 3.7 m (12 ft) and 4.6 m (15 ft) diameter fingerling tanks, the next group is ready to be ponded in six of the twelve 1.2 m (4 ft) diameter fry tanks. When fingerlings reach a size of at least 30 g they are transferred to the West Virginia Aqua LLC Rockhouse Springs Arctic Char Farm for grow-out.

4.3. Conclusions

Local investors in a larger commercial fish farming venture—West Virginia Aqua LLC—have leased the MCRA Hatchery and are managing all aspects of its operation, although MCRA retains ownership. The hatchery's annual production capacity is now about 500,000 to 1 million fingerlings, depending upon the size of the fish when harvested. Therefore, West Virginia Aqua can potentially use the MCRA Hatchery to supply all the fingerlings required to locally produce 600–1300 mt (1.5–3.0 Mlb) of 1.3 kg Arctic char annually.

5. West Virginia Aqua LLC

5.1. Background

In January 2001, West Virginia Aqua began construction of the Rockhouse Springs Fish Farm just outside of Man, WV. The Rockhouse Springs Fish Farm was designed by PRAqua Technologies Ltd. (Nanaimo, BC, Canada) and JLH Consulting Inc. (Courtenay, BC, Canada). The design is based largely on the cold-water recirculating system technology developed at the Freshwater Institute. The facility was constructed using local contractors, except for certain specialized fish culture components that were supplied and installed by Marine Biotech Inc. (Beverly, MA).

The new grow-out farm is supplied with fingerling Arctic char produced at the MCRA Hatchery. The Arctic char are raised to food-size, which is roughly 1.3 kg (3 lb) per fish. If the Arctic char remain healthy, West Virginia Aqua has the capacity to produce about 200 mt of Arctic char annually (0.44 Mlb per year).

5.2. Recirculating systems and wastewater treatment

The Rockhouse Spring Fish Farm was installed with three fully-recirculating systems (Figs. 13 and 14). Each system contains four 6.1 m (20 ft) diameter tanks (with about

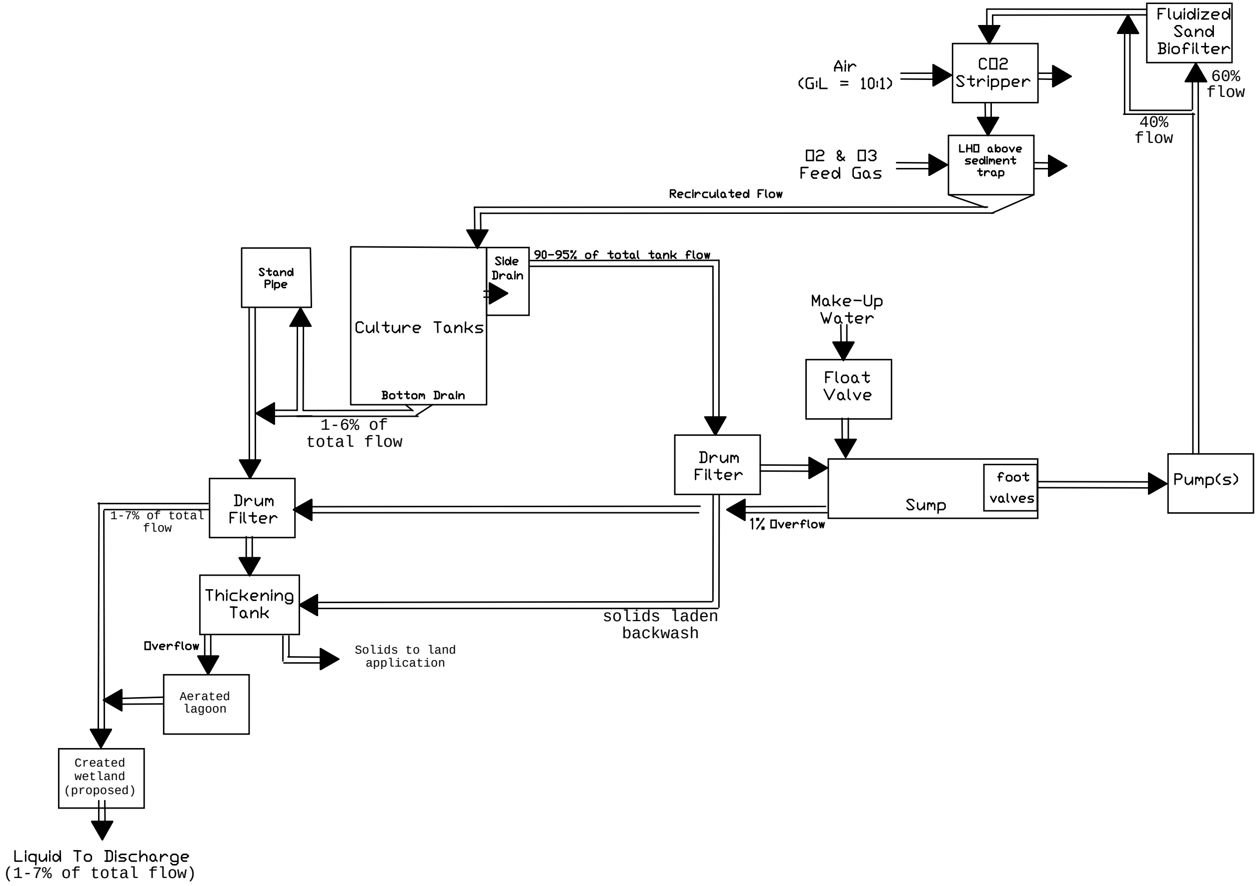

Fig. 13. A process flow drawing of one of the 11,300 l/min recirculating systems at West Virginia Aqua’s Rockhouse Springs Grow-out Farm (Man, WV).

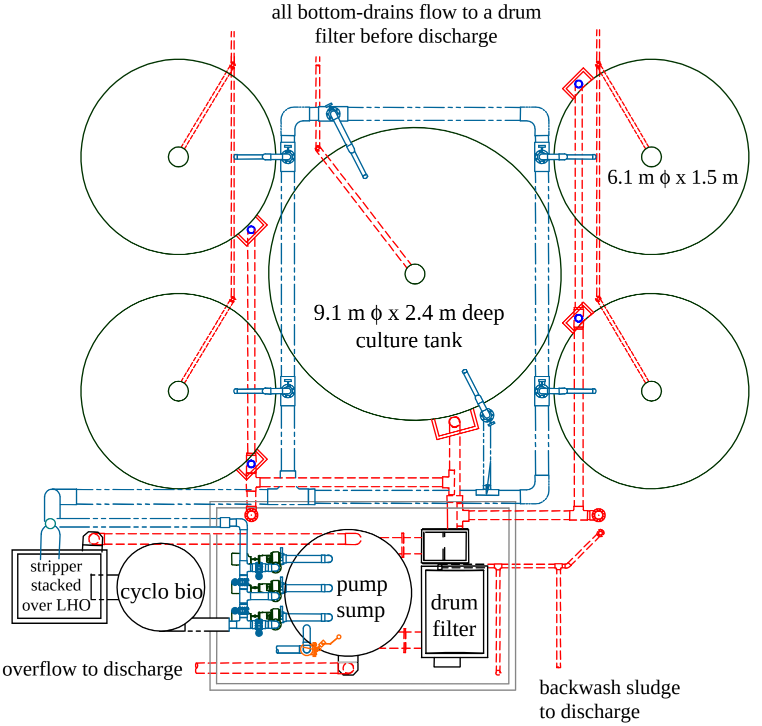

Fig. 14. One of the three 11,300 l/min recirculating modules at West Virginia Aqua's Rockhouse Springs Grow-out Farm (Man, WV). Drawing courtesy of PRAqua Technologies Ltd. (Nanaimo, BC, Canada).

40 m^3 of culture volume in each tank) and one 9.1 m (30 ft) diameter tank to provide a total of 300 m^3 culture volume per recirculating module (Fig. 14). Each system uses two centrifugal pumps to recirculate 11,300 l/min (3000 gal/min), which exchanges the entire culture volume within each recirculating system just over twice every hour. Roughly 60% of the recirculating water is pumped through a Cyclo Bio^{TM} fluidized-sand biofilter while the remaining 40% of the water is pumped directly to the top of the cascade aeration column (Figs. 13 and 14). Otherwise, water treatment is similar to that described at the Freshwater Institute, except that no UV irradiation units or swirl separators are installed at the Rockhouse Springs facility and the water discharged from the bottom-center drain of each culture tank is not returned to the recirculating system (Fig. 14). Water quality has been well within safe limits for unionized ammonia, dissolved carbon dioxide and dissolved oxygen concentrations (Table 2). Also, ozone added in the LHO units has helped to maintain relatively low levels of suspended solids and nitrite nitrogen concentrations (<0.1 mg/l) in the culture tank (Table 2).

The grow-out farm uses 400–2400 l/min (100–600 gal/min) of make-up water, which amounts to 1–7% of the total recirculating flow. The make-up water is captured as it overflows from abandoned mine portals and is piped to the grow-out farm. However, make-up water flows and temperatures are inadequate in the summer to maintain water temperatures in the recirculating systems below 15–16 °C, so water chillers were installed on each recirculating grow-out module. The chillers are used to maintain water temperatures below approximately 13 °C.

Nearly all of the water overflowing from these recirculating systems is discharged from the bottom drains of the system's 'Cornell-type' dual-drain tanks. This effluent is treated across a microscreen drum filter (Fig. 13) before the water is discharged. The biosolids captured in the facility's drum filter backwash are thickened in a clarifier and the supernatant coming off this clarifier is further treated in an aerated lagoon. The farm is also considering installation of a created wetland to polish the entire effluent flow before it is discharged.

5.3. Conclusion

West Virginia Aqua began selling food-size Arctic char in the spring of 2002. However, West Virginia Aqua has faced some challenges obtaining Arctic char that are suited to their warmer water temperatures and that maintain rapid growth to market size. West Virginia Aqua has realized good growth using Tree River × Nauyuk hybrid Arctic char supplied by Icy Waters (White Horse, Yukon, Canada) and an all female brook trout × Arctic char hybrid supplied by Alleghanys Fish Farm Inc. (St. Philemon, Que., Canada). By 2003, the rate of food-fish production at West Virginia Aqua has begun to approach their stated goal of 200 mt per year.

6. Glacier Springs (Manitoba, Canada)

6.1. Background

Glacier Springs Fish Farm (near Gunton, Manitoba, Canada) was founded in 1996 when the firm acquired the Rockwood Institute from the Department of Fisheries and Oceans. In 1997, part of the farm was converted to a 70 tank (2270 l per tank) water reuse system in order to raise the temperature of the 6–8 °C ground water to 10–13 °C, which would be better suited for producing fingerling char.

6.2. Recirculating systems

The nursery system built at the Glacier Springs Fish Farm was designed by Clifton Associates (Regina, Saskatchewan, Canada) and by fish farm staff. The design was based largely upon the cold-water recirculating system technology developed by the CFFI. In this recirculating system the water discharged from the bottom drains of the culture tanks was collected and passed through a drum filter before the flow entered a pump sump. Recirculating pumps then lifted approximately 4800 l/min (1250 gal/min) through two fluidized-sand biofilters (Fig. 15) operated in parallel (Summerfelt and Wade, 1998). Either fluidized-sand biofilter could be shut down when fish were small or when flow requirements were low. Water discharged from the top of the fluidized-sand biofilters then flowed by gravity through an air-stripping column followed by a LHO unit (Fig. 15). Water was further treated with a UV irradiation unit before it was returned to the culture tanks. As originally designed, the recirculating water flow rate would have been sufficient to exchange the tank volume in 40 culture tanks more than twice every hour. However, as the demand for culture volume

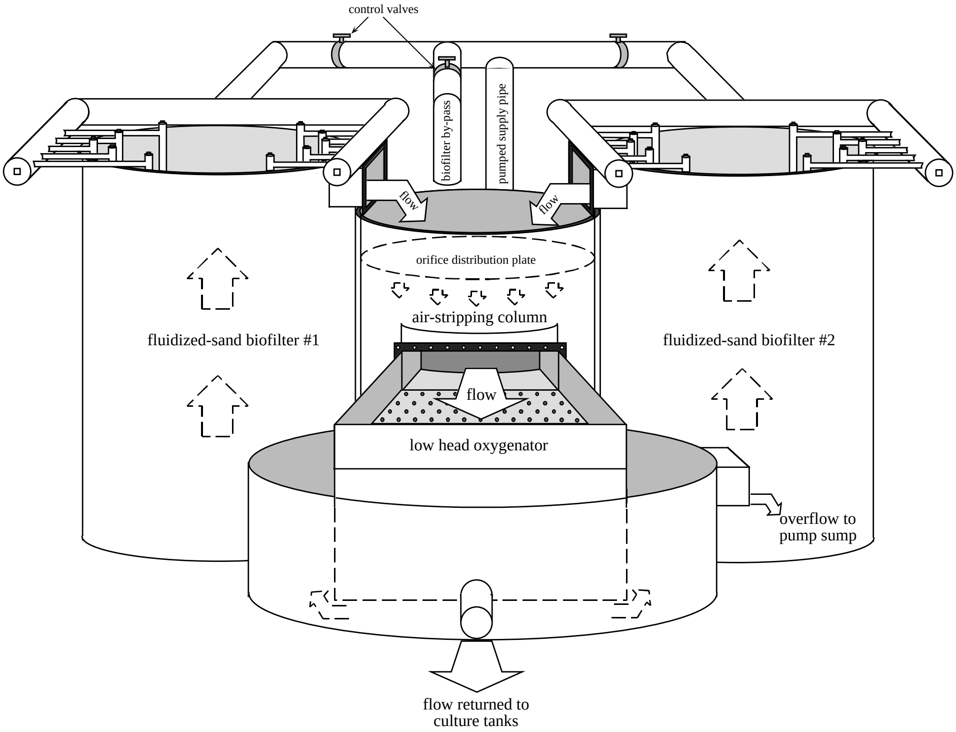

Fig. 15. Water pumped through two fluidized-sand biofilters tumbles by gravity through a forced-ventilation cascade aeration/stripping tower followed by a LHO unit in a recirculating system at Glacier Springs Fish Farm (Gunton, Man., Canada) that treated 4800 l/min (1250 gal/min) in a 70-tank water reuse system (Summerfelt and Wade, 1998).

increased during the construction of this system, modifications to the plan resulted. The final system ran the equivalent of 70 tanks that were each 2270 l (600 gal), which reduced the mean culture tank exchange rate to about once every 40 min—still quite good. During the initial construction, the LHO was installed with the other major components within the recirculating system. However, the oxygenation system was not installed, because its installation was planned for a second expansion phase. This second phase was to include installation of a second large recirculating system that was intended to grow the Arctic char to food size. As the start of this construction was postponed, water could only be aerated through the cascade column to bring dissolved oxygen concentrations to near saturation, but supersaturated levels of dissolved oxygen could not be produced without addition of purified oxygen within the LHO unit. Also, ozone was not added because the oxygen feed gas that carried the ozone (and the ozone generator) were not installed and were delayed until the second expansion phase.

The system was designed to run at mean fish densities of 60–80 kg/m^3, with a peak of 120 kg/m^3. However, as the second stage of expansion was further delayed, fish densities in many tanks were pushed to 250 kg/m^3 as the recirculating system supported a total biomass of over 19,000 kg, i.e., an average system density of 120 kg/m^3. Despite this, the mortality levels were low, with fish mortality at peak stocking density only reaching 0.156% per month (381 morts out of 244,678). Feeding levels were moderate due to the limited space and dissolved oxygen, which also reduced the solids loading on the system. Feeding was done by hand. Make-up water was added at about 5% of the total recirculating flow and water temperatures were increased by 1–2 °C due to ambient heat gain within the building. Water testing was rarely done, as no problems existed with the water quality, fish health or mortality levels. Dissolved oxygen levels at these temperatures were more than adequate, with adjustments for aeration made to the flow via the overhead spray bars at each tank. However, without supersaturated dissolved oxygen concentrations, water flow was in high demand to maintain dissolved oxygen levels within the culture tanks. Reduced water flows were noted at the farthest tanks when the system was heavily loaded. This was most noticeable after shut downs or brown outs. In addition, fungal mat growth in the distribution piping would break free and occasionally clog the spray bars, particularly in these farthest tanks that received the least flow. However, a scheduled flushing of the spray bars and lines was initiated to flush the fungal mats from the pipelines and this cleaning routine helped to maintain flow through the spray bars.

Another modification from the original plan was the downsizing of the discharge and return lines from the fish culture tanks to the drum filter. The undersized drain pipeline resulted from an effort to utilize the present discharge drainage gutters, which would not accept larger pipes and would have had to have been replaced. With the existing floor concrete being 10 in. thick, it was a big enough project (and over budget item), to cut through to install the drum filter and sump without having to cut out and replace the existing floor trenches. It was thought that 10 cm (4 in.) pipes feeding into a 30 cm (12 in.) collection pipe would be sufficient to carry the water flowing from the culture tanks to the drum filter. However, the under sizing of the 10 cm drain pipe was evident over time, especially as fungal mats built up within the pipes. In addition, the 12 in. common drain line did not have any cleanouts, making the flushing of fungal mats from this drain line a challenge. In spite of these pipeline-cleaning issues, in comparison to the 60 individual ‘gravel bed filter and culture tank’ recirculating systems that came with the facility and were used in the old part of the farm, operation and maintenance of the new fluidized-sand bed recirculating system required little effort. The old gravel bed tank system required approximately >20 h^{-1} a week to backwash and maintain.

6.3. Conclusion

The recirculating system was operated for about 3 years; however, Glacier Springs Fish Farm was forced to close when provincial funding, that had been expected, was unavailable to complete the installation of a second large recirculating system. Glacier Springs has been replaced by Agassiz Aqua Farms.

7. Millbrook First Nation Band

7.1. Background

The decision to pursue the development of an aquaculture facility by the Millbrook First Nation Band is part of a broad strategic move by the Band to exercise the First Nation’s

Constitutional Right as reaffirmed by last year's Supreme Court Decision in the Marshall Case confirming the rights of First Nation's People to access the commercial fishery in Nova Scotia and to develop potential aquaculture operations. Millbrook First Nation viewed their entry into the aquaculture sector as a means to economic development for the Band members and to provide rewarding sustainable careers and employment for those living on the reserve. After conducting a feasibility study, it was concluded that a land-based recirculation facility focusing on the culture of Arctic char would be the starting point for the Band's entry into the aquaculture sector. To achieve these objectives, a facility has just been constructed to produce 100 mt annually. The facility was designed in a manner intended to minimize any environmental impacts. Therefore, the facility was designed to operate on a high level of recirculation (99.7% of flow) to reduce make-up water requirements and consequently produce low volumes of waste effluent. In addition to the aquaculture facility, a hydroponic greenhouse operation has been planned to receive a small side stream of the systems recirculation water for the culture of Native Healing Herbs in flood and drain growing systems as well as Native Nursery plants. The intent of the facility is to evolve towards a zero discharge or zero impact facility with the expansion of the greenhouse facilities and greater usage of system wastewater and solids.

CBCL Limited and Canadian Fishery Consultants Limited (a division of CBCL Limited) were contracted by Millbrook First Nation to undertake a feasibility study to arrive at a choice of facility, site, species and scope of project. This was completed by 2001. CBCL Limited then conducted a design brief for the 100 mt Arctic char facility. Several recirculating system and equipment suppliers were contacted to submit quotes on the system. The successful bidder (PRAqua Group, Nanaimo, BC) was then contracted to work with the design team at Qualtech Building Solutions (the successful General Contractor) to supply and install the recirculation systems. Qualtech Building Solutions designed the building and all associated infrastructure. Construction of the facility was completed in the summer of 2003.

7.2. Recirculating systems

Two separate recirculation grow-out systems were installed. By having multiple recirculation systems the capital costs are increased but the biosecurity level is also increased, as is the ability to operate the individual rearing systems under different culturing conditions. In particular, water temperatures in the individual systems will be controlled independently to accommodate a wide range of freshwater species including salmonids, stripped bass, and tilapia. However, the recirculating systems were designed to produce water quality suitable for producing food-size Arctic char. Therefore, the recirculating systems are expected to be more than adequate at maintaining water quality for other species that may not be as sensitive to water quality as salmonids. With this facility, the choice of fish species can be 'market driven' and the species produced can be changed to respond to changes in the market.

The recirculating system for the Millbrook First Nation facility was designed to operate under much lower exchange rates (to accommodate the variable temperature control requirements) than the other recirculating culture systems described in this paper and will incorporate foam fractionation with ozonation and heat transfer coils but not UV irradiation units. Each recirculation system is comprised of five round tanks (two 5 m diameter tanks;

two 9 m diameter tanks; one 11 m diameter tanks) each with a 2 m tall side-wall. The culture tanks were designed to accommodate varying water depths, but at a water depth of 1.85 m the total culture volume in each recirculating system is approximately 480 m^3. Culture tank turnover time is approximately 45 min. The maximum stocking density will be 85 kg/m^3. Tanks for the system were constructed out of ‘Octoform’ building material, which is comprised of a PVC ‘leave in place’ form filled with concrete. The varying tank sizes allowed for greater utilization of floor space and increased flexibility in stock management. Each tank was installed with ‘Cornell-type’ double drains. The side drain passes a high volume of low solids water. The bottom drain passes a low volume of high solids water. The proportional split between the two drains is dictated by a minimum bottom flow at a rate of 6 l/min of flow per square meter of tank area (0.15 gal/(min ft^2) of tank area). With the tanks described above, the total flow is approximately 10,545 l/min (2790 gal/min) of which approximately 2109 l/min will come from bottom drains and 8436 l/min will come from side drains.

The water leaving the culture tanks through the bottom drain is rich in solids. This stream of water first passes through a tank-side swirl separator (each tank has its own swirl separator). Individual swirl separators allows for observation of waste products from the tank as well as increasing settling of solids by keeping the solids intact. The overflow from the swirl separator joins the side drain water and flows to the microscreen drum filter by gravity. The microscreen drum filter is installed with 90 μm sieve panels. This drum filter is back washed only intermittently, requiring approximately 23 l/min (6 gal/min). The waste backwash water from the swirl separators and the drum filters is combined and then discharged to the municipal sewer system.

The water leaving the drum filter flows across a weir wall and is spread out over a large distribution plate allowing it to be broken up and fall into a 3.7 m (12 ft) deep filtration chamber. The first 0.9 m (3 ft) fall through the chamber (below the distribution plate) is open and is fed with 76 m^3/min (2700 scfm) of air, which travels the entire length of the chamber before exiting via a PVC duct. This serves to strip the carbon dioxide from the water. The water then continues to fall through the next 0.9 m of the chamber, which contains floating polystyrene beads. This section serves as the main biofilter, converting ammonia waste into nitrite and then nitrate. The remaining 0.9 m of the chamber is flooded with water to prevent the polystyrene beads from flushing out the bottom of the chamber. Water exiting this chamber travels over a weir wall and enters a pump sump. From this sump water is pumped back to the tanks via a main line (fed from two 10 hp pumps) and a second line that is supersaturated with oxygen. Water height, pH, ORP, and temperature are also monitored in this sump. The variable speed drive pump are controlled to maintain water level in the sump. Temperature is controlled via a hot water heat exchanger in the pump sump and external chillers operating on a side loop. Heat is supplied from oil fired boilers.

Water from the pump sump is also drawn off via a side stream and passed through foam fractionators. Air and ozone are injected via a venturi into the foam fractionators to increase the removal of fine solids from the system. Water from the foam fractionators is returned to the system at the base of the carbon dioxide exit duct. This allows any ozone off gassing from the water to vent from the system. Ozone is generated using a 90% pure oxygen feed gas, which is generated onsite using a pressure-swing absorption unit.

The new water entering the system comes from one of two sources. The primary source is from wells drilled on-site. The secondary water source is from a municipal water supply.

Well water is the preferred source of make-up water because it does not contain chlorine and it has a more constant water temperature (8–10 °C), which is nearer the desired culture temperature (12 °C) than the municipal water. The municipal water can vary in temperature from 4 °C in the winter to 19 °C in the summer. This wide range in temperature requires either heating or chilling to reach the desired culture temperature of 12 °C. Well water is supplied from a 300 ft deep well and enters the system at the stripper distribution plate. Back up water is available from a municipal supply.

The system is designed to produce 125 mt of head-on-gutted Arctic char per annum and has a design standing stock capacity of 70,000 kg. It is designed to handle ammonia and carbon dioxide production, and oxygen requirements of a standing stock of 35,000 kg per system (70,000 kg total) and metabolism of 350 kg feed per day per system (700 kg per day total).

Lighting over each of the tanks can be controlled via dimmers to influence maturation and feeding responses.

All of the systems are housed within an enclosed building constructed from insulated concrete form structures. The inside of the building was paneled with 'choroplast' plastic panels making for a completely waterproof and washable finish. The concrete shell provides a large thermal mass that moderates against temperature swings inside the building. In addition to containing the recirculating culture systems, the building houses other areas for feed storage, shipping/receiving; stunning/bleeding, electrical and mechanical rooms, ice storage, office areas, and a lunch room.

7.3. Conclusions

The aquaculture facility is located directly adjacent to the newly developed Power Center in an industrial/commercial park area located adjacent to the main highway (between Halifax and Truro) just outside of Truro called the "Millbrook Power Center". Construction of the facility was just completed in the summer of 2003. The first cohort of Arctic char fingerling to be stocked into the facility is being reared at a small recirculating facility within 15 km of the facility. It will be interesting to follow the operation and performance of this facility to evaluate the efficiencies of its design and operation.

7.4. Overall conclusions

Discussing the economic viability of Arctic char production within recirculating systems was never an intention of this paper. However, this paper does note that problems with the design of recirculating system can preclude success even at a demonstration facility (i.e., the Daniel's Harbour Arctic Char Project) and that problems with fish pathogens can reduce survival and feed levels (i.e., at the CFFI) to the point that economic success would become a problem if the fish health problems continued. Undercapitalization was another problem that can limit success (as at the Glacier Springs Fish Farm). Therefore, many challenges can limit success at commercial recirculating aquaculture facilities. This paper has focused on the challenges that can be overcome through system design.

Clearly, there is no single recirculating system design that can be used for every fish culture application, due largely to the many different variables involved in the design, including widely different water requirements for dissimilar species at various life stages. However, even for a single species such as Arctic char, this paper showed that there are still some important differences (and quite a few similarities) in the recirculating system design used. Several of these similarities and differences are summarized in Table 2. It appears that the more recent recirculating systems for Arctic char production have been improved in order to improve the water quality that the systems can maintain at high feed loadings and also to increase the production capacity of these systems. Several key process improvements include increased hydraulic exchange rates through the culture tank, superior culture tank designs, better oxygen control strategies and ozonation, improved design of forced-ventilated cascade aeration columns, full flow drum filtration, and better pipe and sump cleanout designs. These key process improvements are described in more detail below.

7.5. *Increased water flow and oxygen use*

One of the biggest improvements in the recirculating system designs has been to increase the recirculating system's pumping rate in order to exchange the culture tanks once every 30–45 min, which increases the mass of oxygen transported and increases the waste flushing rate from a given culture volume. Note that hydraulic exchange rates are typically more rapid through fry and fingerling culture tanks than through grow-out tanks (Table 2), because smaller Arctic char consumer a higher percentage body weight of feed than fish approaching food size. A relatively long hydraulic exchange (i.e., one exchange approximately every 112 min) through the culture tanks at the Daniel's Harbour Arctic Char Facility was a primary reason that the facility had difficulties supplying dissolved oxygen and controlling accumulations of carbon dioxide.

Intensification with oxygenation and increased culture tank exchange rates increases fish production in a given physical area, which in turn reduces the volume of culture tank required and the system footprint that must be covered by an expensive building. However, intensification through oxygen supplementation also increases the waste load in the water. The dissolved oxygen consumption across the culture tank cannot be too great or so much dissolved carbon dioxide and total ammonia nitrogen will be produced within the culture tank that it becomes difficult to maintain water quality within limits considered safe for the fish. Once dissolved oxygen is no longer limiting, then other fish metabolites can limit culture tank carrying capacity. Fish produce approximately 25–35 g of total ammonia nitrogen, 300–400 g of carbon dioxide, and 250–400 g of total suspended solids for every 1.0 kg of feed consumed. In terms of dissolved oxygen consumption, however, fed fish produce roughly 1.0–1.4 mg/l total ammonia nitrogen, 13–14 mg/l dissolved carbon dioxide, and 10–20 mg/l of total suspended solids for every 10 mg/l of dissolved oxygen that they consume (Summerfelt et al., 2000c). Therefore, dissolved carbon dioxide and unionized ammonia concentrations can rapidly accumulate to toxic levels when fish consume large concentrations of dissolved oxygen within the culture tank.

In general, salmonids can use the water flow without worry of ammonia or carbon dioxide limitations (assuming no biofiltration or air-stripping) up to a cumulative dissolved oxygen consumption (ΔDO) of up to 10–20 mg/l (Colt et al., 1991), depending upon pH, alkalinity, temperature, fish species and life stage. Treatment processes in recirculating systems are not 100% efficient, therefore, the ΔDO across the culture tank should be limited to about

10 mg/l for salmonids. Also, supplying a maximum ΔDO of 10 mg/l across the culture tank is consistent with the use of LHO's (because LHO's perform best when providing dissolved oxygen at concentrations that are less than twice the saturation concentration, i.e., roughly 20 mg/l at 15 °C) and this is one of the reasons why most of the Arctic char facilities described in this paper used LHO to supersaturate the water flow with oxygen directly before the water entered the culture tanks.

Although not mentioned in the case studies described above, micro-bubble diffusers were used to sparge—upon demand—purified oxygen gas (supplied from liquid oxygen tanks) directly into the culture at all but one (Glacier Spring Fish Farm) of the Arctic char culture systems described in this paper. The micro-bubble diffusers connected to the liquid oxygen supply were a back-up oxygen control method that was only implemented to keep fish alive in the event that water flow to the culture tank was lost due to pump or power failure. For example, the backup oxygen system at the CFFI used solenoid valves that were automatically opened upon loss of water flow to send oxygen gas to the culture tank diffusers. However, most of the other facilities described above used 24 h surveillance and float switch alarms to notify staff that water flow had been lost. Staff would then respond by manually opening valves to send oxygen gas to the culture tank diffusers upon loss of water flow. Note that in all instances gas was never continuously sparged through the diffusers into the culture tank for the purpose of oxygenation or aeration. Continuous use of the diffusers for oxygenations would be a mistake because oxygen transfer efficiencies are typically quite low (often $<15\%$) when using diffusers within relatively shallow fish culture tanks (Carmichael et al., 1992) and this would be an inefficient manner to supplement dissolved oxygen. For another reason, the authors' experiences have shown that continuous use of diffusers within the culture tank will float and break apart solids and significantly degrade water quality within the recirculating system. Depending upon the type of fine bubble diffusion systems in use, the diffusers may require service to prevent them from becoming fouled and plugged if they are continuously submerged within the culture tanks.

When oxygen supplementation is required at individual culture tanks, then some farms with multiple culture tanks (e.g., the Millbrook First Nation Arctic Char Facility) have incorporated a side-stream system to add a relatively high concentration of dissolved oxygen to a relatively small water flow. This type of supplemental oxygenation system may use a relatively high pressure pump and a down-flow bubble contactor to super oxygenate a side stream of water (anywhere from 10–40% of total tank flow), which is then distributed among the culture tanks as required to meet the specific oxygen demands of each culture tank.

7.6. Carbon dioxide control

Dissolved carbon dioxide tends to accumulate within recirculating aquaculture systems because the pure oxygen supplementation technologies increase the feed and fish loading rates in these systems (as explained above) and the oxygen transfer devices used do not provide sufficient gas exchange to remove a great deal of the dissolved carbon dioxide produced (Watten et al., 1991). Problems with dissolved carbon dioxide did occur in the recirculating aquaculture system at the Daniel's Harbour Arctic Char Farm (Table 2), most likely because of difficulties achieving the high gas-to-water loading rates necessary for more effective carbon dioxide stripping. However, improvements have been made in dissolved carbon dioxide control methods used in cold-water recirculating systems and the Arctic char culture facilities built after the Daniel's Harbour Arctic Char Farm have benefited from these improvements in stripping column design. Forced-ventilation cascade columns are now designed to contact large volumes of air (as much as 10 volumes of air per volume of water) with cascading water to increase the carbon dioxide removal efficiency provided by technologies that provide lower air-to-water contact rates (Grace and Piedrahita, 1993, 1994; Summerfelt et al., 2000b, 2003). For example, forced-ventilation cascade columns containing 1 m of packing depth that supplied 10 volumes of air flow for every 1 volume of water flow have been found to remove roughly 40–60% of the dissolved carbon dioxide each pass in cold-water recirculating systems (Summerfelt et al., 2000b, 2003). Random packing (Summerfelt et al., 2000b) was found to produce higher carbon dioxide removal efficiencies than structured packing (Summerfelt et al., 2003), but may be more likely to plug from an accumulation of biosolids. Some of the forced-ventilation cascade columns (e.g., the units at West Virginia Aqua) did not contain any packing but were provided with approximately 50% of additional cascade height to maintain effective carbon dioxide stripping. Providing large air volumes to cascade columns has proven to be relatively inexpensive when low-pressure and high volume air-handling fans are used (Summerfelt et al., 2000b, 2003). Therefore, in addition to the recirculating systems used for Arctic char production, many of the more recent cold-water recirculating systems used salmon smolt production in North America have been supplied with forced-ventilation cascade columns designed to achieve high air-to-water contact rates.

Note that a biofilter can produce 37% of the total dissolved carbon dioxide produced within a recirculating salmonid system (Summerfelt, unpublished data). Therefore, placing the carbon dioxide stripping unit after the biofilter is a sensible option to minimize the amount of carbon dioxide that enters the fish culture tank. When the stripping unit is placed before the biofilter (as in the Millbrook First Nation Arctic Char Facility), then the fish will encounter a dissolved carbon dioxide concentration that will be 20% greater than if the stripping unit were placed immediately after the biofilter (as in all of the other Arctic char production facilities discussed above). Also, the stripping column at the Millbrook First Nation Arctic Char Facility does not contain packing within the 0.9 m cascade, so the efficiency of stripping will also be lower than that found at the CFFI and West Virginia Aqua. In recirculating systems, the concentration of carbon dioxide exiting the culture tank will be inversely proportional to the efficiency of carbon dioxide stripping (Liao and Mayo, 1972). Therefore, if all else remains the same (e.g., feeding rate and culture tank exchange rate), a recirculating system containing a more efficient stripping columns will provide at lower steady-state carbon dioxide concentrations within the culture tank than a recirculating system containing a less efficient stripping column.

7.7. Solids control

Inadequate solids control can seriously compromise water quality within a recirculating system. In the Daniel's Harbour Arctic Char Project, the solids removal system had three serious problems with solids control that ultimately deteriorated water quality: (1) the dual drains located in the center of the culture tank did not fractionate solids effectively; (2) the bulk of the water discharged from the culture tank was not microscreen filtered; (3) solids accumulating in the settle-deck sump were mineralizing within the recirculating system, potentially harbouring opportunistic fish pathogens, and exerting a large oxygen demand on the system. The other recirculating systems described above for Arctic char production maintained good to excellent solids control, probably because:

(1) The 'Cornell-type' dual-drain tank appears to effectively and rapidly fractionating settleable solids (Summerfelt et al., 2000a,d). Because the elevated drain in the 'Cornell-type' design is part-way up the tank side-wall, the elevated drain in a 'Cornell-type' tank does not capture many of the solids that sometimes "plume" up in the center of circular culture tanks that are operated with both dual-drains located in the center of the tank.
(2) All of the water discharged from the culture tank was passed through drum filters before being reused within the recirculating system.
(3) Solids removal technologies were avoided that intentionally stored solids for more than several minutes within the recirculating system.

In addition, several of the recirculating systems reported problems created by solids deposition within the systems pipes and sumps. These problems were aggravated if cleanouts on pipelines and sumps were lacking or difficult to access. The solids accumulation problem arises when water velocities are inadequate to prevent solids from settling in pipes and sumps, or when the water velocity is insufficient to strip the thick fungal/filamentous growth off the pipe and sump walls. In order to have reduced these problems, meticulous attention to detail is required when selecting the size, slope, and pipe cleanout points during the design of a recirculating systems, because these details not only influence the water transmission, but they also influence how "free" from solids the system can be maintained (Summerfelt et al., 2001). All pipes, channels, and stand pipes should be sized to produce a water velocity of at least 0.7–1.0 m/s at the design flow rate when water is flowing by gravity. Pipe should be flushed frequently (daily or weekly) and sometimes brushed to further reduce solids deposits and biofilm mat growth within pipes. The recirculating system must also be designed so that the water flushed from pipes during cleanout periods can be discharged outside of the recycle system so that these routine flushing operations do not degrade water quality in the culture tank. Good examples of well-designed pipeline and sumps cleanouts can be seen at the CFFI in Shepherdstown, WV, and at the MCRA Hatchery in Delbarton, WV.

Additionally, to handle cleaning flows, the drum filters treating the side-wall drains should be oversized by at least 50% over the normal design flow (1.5 times design flow) and the drum filters treating the bottom drain flows should be oversized by at least 200% over the normal design flow rate. If a drum filter cannot handle the cleaning flow, the solids laden water can overflow the drum to the pump sump, which seriously degrades water quality. Providing excess drum filter capacity is not that much more expensive when installed up front (with respect to the total project cost) and these oversized drum filters can better handle the cleaning flows created when the culture tank stand pipes are pulled.

7.8. Ozonation

The fully-recirculating systems at West Virginia Aqua and the CFFI[2] (at times) have used ozone addition within the system LHO to help maintain good to excellent water

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[2] The partial-reuse system at the CFFI did not require ozonation to maintain excellent water quality.

quality (Table 2). Ozone will also be added in the foam fractionator in the recirculating systems for the Millbrook First Nation Band (Table 2). Ozone is added to enhance fine solids removal, possibly by changing particle size (i.e., microflocculating fine particulate matter) and surface properties, which can make particles easier to settle, filter, or float (Summerfelt et al., 1997). Ozone is also added to these recirculating systems to improve water quality by oxidizing nitrite to nitrate and oxidizing larger and relatively complex organic molecules and thereby creating smaller and more biodegradable molecules. However, the ozone demand of water within recirculating aquaculture systems, which contains much higher levels of organic material and nitrite, creates a short ozone half-life (e.g., less than 15 s) and makes maintaining an ozone residual difficult (Bullock et al., 1997). For this reason, achieving large microorganism reductions in recirculating systems requires greater ozone dosages than are required for simply controlling water quality within these systems (Bullock et al., 1997) and also much higher ozone dosages than are typically required for disinfecting single-pass inflows (Summerfelt, 2003).

7.9. Culture tank design

Overall, the large circular culture tanks using ‘Cornell-type’ dual-drains appear to have maintained relatively uniform water rotational velocities, rapid and effective solids fractionation, and good hydraulic mixing properties. However, it is evident that supplying a water flow to produce at least one tank volume exchange every 30–45 min is necessary to carry oxygen to the fish while flushing waste metabolites. Additionally, a ‘Cornell-type’ dual-drain culture tank must also have sufficient water flow through its bottom drain to rapidly and completely flush settleable solids that are moved to the center of the tank by the secondary radial flow that is created by the tank’s primary rotating flow (Timmons et al., 1998; Summerfelt et al., 2000c). Further experience at the CFFI has shown that to achieve optimum solids flushing hydraulics within ‘Cornell-type’ dual-drain culture tanks, approximately 6 l/min of water flow is required through the bottom drain for every 1.0 m^2 of the tank’s plan area. At lower surface loading rates the bottom drain standpipe may have to be pulled several times each day to flush solids that have accumulated about the center drain sump.

Achieving effective hydraulic mixing within the ‘Cornell-type’ dual-drain tanks is especially important to prevent water flow from short circuiting directly from the tank inlet to the tank side-wall drain by flowing in a plug about the circumference of the tank. However, ‘Cornell-type’ dual-drain culture tanks are being designed with special inlet structure features and orientation to create effective hydraulic mixing, optimum rotational velocities, and good solids flushing (Timmons et al., 1998). Good examples of effective inlet structure design can be seen at the CFFI.

Fish farm designers must remember to consider how the occasional dead fish will be removed from the bottom-center drain of circular culture tanks that are relatively large and deep, e.g., the mort flush system in use at the CFFI (Fig. 6). Designers should also consider methods that can be used to simplify or automate fish size sorting during harvest, e.g., using a clam-shell grader and an airlift fish pump with a hand-sorting box at the CFFI (Fig. 7).

7.10. Biofiltration

Fluidized-sand biofilters were used in all the recirculating systems for Arctic char culture facilities that were discussed above, except for the most recent facility just completed for Millbrook First Nation Band. However, three different varieties of fluidized-sand biofilters were used and all seemed to have worked well. The CFFI and West Virginia Aqua used Cyclo Bio^{TM} fluidized-sand filters supplied by Marine Biotech Inc. (Beverly, MA). The Glacier Springs Fish Farm used a modified pipe-lateral design to inject water flow under the sand bed. The Daniel's Harbour Arctic Char Project used a false-floor design to distribute flow. General details on these types of fluidized-sand biofilter are provided elsewhere (Summerfelt and Cleasby, 1996; Summerfelt et al., 2001). Fluidized-sand biofilters were probably selected because filter sand is relatively inexpensive (approximately US$ 40–70/m^3) and has a high specific surface area (8000–12,000 m^2/m^3), which reduces the cost of surface area (approximately US$ 0.003–0.009/m^2 surface area) and makes fluidized-sand biofilters exceptionally compact (Summerfelt and Wade, 1998; Summerfelt et al., 2001). Fluidized-sand biofilters can also be designed to treat large flows, with existing units treating 11,000 l/min of water flow. For these reasons, large fluidized-sand biofilters can be exceptionally cost competitive compared to other large-scale biofilters (Summerfelt and Wade, 1998; Timmons et al., 2000), even when constructed with excess nitrification capacity. Fluidized-sand biofilters are also efficient at removing ammonia, typically removing 70–90% of the ammonia each pass in cold-water recirculating systems, and maintain low nitrite levels. Typical fluidized-sand biofilter outflows will often only contain 0.1–0.5 mg/l of total ammonia nitrogen and $<$0.1–0.3 mg/l of nitrite nitrogen (Table 2).

The recirculating systems for the Millbrook First Nation Band incorporate down-flow polystyrene bead biofilters and these biofilters had not yet been established with nitrifying bacteria at the time this paper went to press. Unfortunately, there is no data published on ammonia removal efficiency across down-flow polystyrene bead biofilters used in cold-water recirculating systems. However, in a warm-water tilapia application, Greiner and Timmons (1998) report that polystyrene bead biofilters provided $<$10% ammonia removal efficiencies.

The biofilter's ability to remove a large fraction of the ammonia each pass has a large influence on the concentration of ammonia that accumulates within a recirculating system. Liao and Mayo (1972) showed that waste metabolite accumulation (e.g., total ammonia nitrogen, total suspended solids, and carbon dioxide) in a recirculating systems is proportional to the rate at which the waste is produced (e.g., kilograms of waste produced per day) and inversely proportional to the efficiency that the water treatment unit processes remove the waste (e.g., the fraction of waste removed each pass) and to the water flow rate being recycled (e.g., cubic meter of flow per minute). Therefore, if all else is equal, a biofilter will maintain a lower concentration of ammonia in the recirculating system if it is more efficient at ammonia removal or if the flow rate through the biofilter is increased. Unfortunately, biofilters are often designed simply to provide sufficient surface area (or bed volume) to remove the mass of ammonia produced each day, with no accounting for the water flow or ammonia removal efficiency across the biofilter. An engineer must consider the biofilter's ammonia removal efficiency and the recycle water flow rate during the design to estimate the accumulation of ammonia within a fully-recirculating system. Thus, for species such as salmonids that require relatively low levels of unionized ammonia, the biofilter's ability to remove a large fraction of the ammonia passing is an important factor to be considered when selecting a given biofilter type.

7.11. Biosecurity

Fish disease problems were not an issue at any of the Arctic char facilities except for the recurring outbreaks of respiratory disease that were encountered at the CFFI. From a biosecurity standpoint, however, these recirculating facilities for Arctic char culture had several advantages:

- Arctic char eggs were imported into the culture facilities (or were spawned on site at Glacier Springs Fish Farm) as certified free from specific listed salmonid pathogens, which significantly improves biosecurity. In contrast, recirculating systems used to produce food-size hybrid striped bass or yellow perch must rely on supplies of extensively reared fingerlings (i.e., from ponds) that might carry any number of fish pathogens into a fish culture facility.
- Relatively small ground water supplies could be used for make-up water addition. Hindsight shows that none of these ground water supplies contained any of the listed salmonid pathogens. The spring pond adjacent to the spring water source at the CFFI was suspected to have been the source of the gram (−) intracellular bacteria that caused the respiratory disease in the pure strain Arctic char, because on occasion pond water was mixed with the spring water pumped into the recirculating facility. Ground water supplies are not sterile and may carry opportunistic fish pathogens. However, a ground water is still less likely than a surface water to carry a fish pathogen that will create serious fish health problems.
- Buildings were used to reduce heat transfer into or out of all the recirculating systems and these buildings also served as effective barriers preventing birds and animals from entering the fish culture waters.

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