



Comparison of hydraulics and particle removal efficiencies in a mixed cell raceway and Burrows pond rearing system



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ABSTRACT

We compared the hydrodynamics of replicate experimental mixed cell and replicate standard Burrows pond rearing systems at the Dworshak National Fish Hatchery, ID, in an effort to identify methods for improved solids removal. We measured and compared the hydraulic residence time, particle removal efficiency, and measures of velocity using several tools. Computational fluid dynamics was used first to characterize hydraulics in the proposed retrofit that included removal of the traditional Burrows pond dividing wall and establishment of four counter rotating cells with appropriate drains and inlet water jets. Hydraulic residence time was subsequently established in the four full scale test tanks using measures of conductivity of a salt tracer introduced into the systems both with and without fish present. Vertical and horizontal velocities were also measured with acoustic Doppler velocimetry in transects across each of the rearing systems. Finally, we introduced ABS sinking beads that simulated fish solids then followed the kinetics of their removal via the drains to establish relative purge rates. The mixed cell raceway provided higher mean velocities and a more uniform velocity distribution than did the Burrows pond. Vectors revealed well-defined, counter-rotating cells in the mixed cell raceway, and were likely contributing factors in achieving a relatively high particle removal efficiency—88.6% versus 8.0% during the test period. We speculate retrofits of rearing ponds to mixed cell systems will improve both the rearing environments for the fish and solids removal, improving the efficiency and bio-security of fish culture. We recommend further testing in hatchery production trials to evaluate fish physiology and growth.

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1. Introduction

Many fish hatcheries have rearing systems that are in need of improvements. Additional factors affecting these systems include changes in production goals, water availability and effluent regulations. However, infrastructure modifications may not be easily executed, and decisions regarding retrofitting must be made carefully. Raceway systems are widely used in many aquaculture operations, especially for salmon and trout production because they can utilize gravity flow to minimize pumping costs, and plug flow (gradient) insures that higher quality water is provided to the rearing system (Westers and Pratt, 1977; Piper et al., 1982; Wedemeyer, 2001; Hinshaw and Fornshell, 2002). However, it is well known that circular tank rearing systems provide a uniform

culture environment, operate well under a wide range of rotational velocities, and provide effective particle removal (Davidson and Summerfelt, 2004; Oca and Masaló, 2013). However, adapting hatchery practices to circular tanks requires different systems for handling and crowding fish, and circular tank layouts are not an efficient use of space. A hybrid rearing unit, the Burrows pond, was developed for trout and salmon culture in the 1960's, designed to incorporate the rectangular plug flow and circular pond into a single rectangular circulating pond (Burrows and Chenoweth, 1970). Flow into the ponds is provided through a series of nozzles at different depths and in corners. However, in several locations where these ponds were installed, the hydraulics and flows were inadequate to remove waste feed and feces.

Recent innovations have been proposed to reduce solids loading from effluents from traditional flow through raceway or pond systems (e.g. MacMillan et al., 2003; Viadero et al., 2005; Stewart et al., 2006; Sindilariu et al., 2009). Watten et al. (2000) proposed the mixed cell raceway system as a modification for existing rectangular raceway or pond systems that would establish a mixed

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flow reactor to improve current velocities and solid scour while eliminating metabolite concentration gradients.

A mixed cell raceway (MCR- Watten et al., 2000) consists of separate cells, each defined by center drains, with inlets that are vertical pipe sections extending from above water level to the tank floor and positioned at the corner of the cells. The number of cells can vary, depending on the relationship of length and width of the cells. The vertical inlet pipes have jetted ports that direct the water into each of the cells tangentially and establish the water circulation. Water exits each cell through a centrally located bottom drain covered with a screen. An outside standpipe regulates the height of water in the system. Ebeling et al. (2005) modified the MCR concept for partial reuse with a 'Cornell type' dual drain system so that solids could be separated easily. In their studies, velocities were high enough to scour, remove and collect solids separate from the return flow. Labatut et al. (2007) measured velocity profiles in each of the cells of a MCR, and found no significant differences between replicate cell velocity contours and vector plots. Recent 3D simulations of a MCR using computational fluid dynamics showed strong correlations and data agreement between the model and measures of velocity at three depths measured (Labatut et al., 2015).

The measures of hydraulic effects and mixing in any system can be described by either a hydrodynamic model or a reactor model (Haan et al., 1994). Hydrodynamic models can be correlated with fish performance and be used to explain feed and feces distribution throughout the system. The models assist in calibrating a system to assure that feed is not removed too quickly, but that waste accumulation is minimized.

Rapid removal of solids from rearing systems can improve overall fish health (De Schryver et al., 2008; Castro et al., 2011), improve bio-security (Oidtmann et al., 2011) and help with regulatory compliance regarding solids discharge (Cripps and Bergheim, 2000; Boyd, 2003). In addition to removing pathogenic bacteria and viruses from accumulating, increasing attention has focused on adjusting rearing systems to reducing the risks of transfer of invasive aquatic species (Oidtmann et al., 2011; Williams et al., 2013; Coppe et al. 2016). Invasive mollusks, such as the New Zealand mudsnail *Potamopyrgus antipodarum*, and zebra/quagga mussels *Dreissena* sp. have become established in source waters of several conservation and commercial fish hatcheries in North America (Sykes et al., 2011; Nielson et al., 2012). Management guidelines and regulations require that the risks of transport be reduced with selected management tools that may include treatments and depuration strategies (Waller et al., 1996; Bruce et al., 2009; Bruce and Moffitt, 2010). With disinfection or depuration tools, it is important that feces and associated waste materials be discharged from the production system to insure that no live materials remain with the fish to be transported.

The objectives of this study were to describe and evaluate a Burrows pond retrofit designed to establish mixed cell behavior within the confines of the existing Burrows pond shell while allowing for operation solely on the limited hydraulic head available at the site. Two full scale test tanks were constructed then compared with two standard Burrows ponds in terms of particle removal kinetics, water velocities and water residence time distributions. Tests of particle removal kinetics were conducted using particle sizes comparable to fish feces as well as the New Zealand mudsnail (NZMS) which is of concern to the National Fish Hatchery Program.

2. Materials and methods

2.1. Location of trials and experimental systems

Studies were conducted at Dworshak National Fish Hatchery, Ahsahka, Idaho. The existing Burrows ponds (BP) allowed for a

maximum depth of 1.5 m (Fig. 1). Water was delivered to the units through two inlet pipes, each with 7 ports at opposite corners of the raceway. A center wall was located 2.9 m from the end walls with a catwalk on top to assist personnel with maintenance of the BP and fish. At opposing ends of the center wall, a floor drain measuring 2.4 m by 0.3 m was used to remove water and solids. The drains were covered with slotted steel panels (60%). The drain boxes emptied into a 30.5 cm effluent pipe that connected to a water level control box containing dual standpipes. One drain section directed the effluent to the hatchery reuse system while the other drain directed effluent to the settling ponds.

Two BPs were modified for our study to create 4-cell MCRs through removal of the BP center walls and installation of four center drains (Fig. 1). These circular drains were screened with a 60% open plate and positioned on a line 30.48 cm from the vessels longitudinal axis which allowed for use of the original BP effluent conduit present below grade. Piping was added above the water line to transport inflow water to down legs in each cell that distributed flow tangentially through four or eight jet ports to establish the counter rotating cells (Fig. 2). Each resulting MCR cell measured 5.72 m long by 5.18 m wide which established a cell specific length to width ratio of 1.1. The overall length to width ratio of the MCR remained unchanged from the original BP configuration, i.e., 4.41. A standpipe in the water level control box was used to control water depth in the MCR. The wetted surfaces of all test rearing units were coated with Krete Kote (Multicoat Corporation, Rancho Santa Margarita, CA) prior to our hydrodynamic evaluations to reduce the shear stress associated with the original pitted concrete surfaces.

To test the hydraulic conditions with fish, Steelhead Trout (*Oncorhynchus mykiss*) were placed into the MCR and BP as sub-yearlings in October 2009 and held until smolt release in April 2010. Each unit was stocked with 31,500 fish. Biomass loadings were estimated from fish sizes at the time of water hydraulic residency trials conducted in November and March (Table 1). To adjust for the displacement of water by fish biomass, we assumed each kg of fish displaced equal L of water.

2.2. Hydraulic characteristics

We initially used computational fluid dynamics (CFD) software and analysis (Blue Ridge Numerics, Charlottesville, VA) to test the ability of the proposed BP retrofit to establish the desired counter rotating cells despite use of the offset center drains and distorted cell dimensions. Initial CFD simulations were performed using the planned MCR design operated under the following 3 conditions of flow rate (m^3/min) and water depth (m): 2.27, 0.91; 2.27, 0.79; 1.89, 0.91. A fourth run was performed with cell drains centered at a flow rate and water depth of 2.27 m^3/min and 0.91 m. All runs provided steady state flow vectors as well as mean velocities established for a grid that included 96,912 points distributed uniformly over the floor area of two adjacent cells of the MCR on a plane 1.3 cm or 34.8 cm above the tank floor. All runs were also performed at a simulated water temperature of 12 °C and with the design pressure drop of 15.2 cm H_2O across cell drains.

Following the CFD runs we established the hydraulic characteristics of the as-built MCR and standard BP test tanks at 3 points in the standard hatchery rearing cycle. Trials were conducted before fish were introduced (September 2009), then with zero-age fish (23 November 2009), and in the spring (18 March 2010) with pre-release yearling smolts. Flows for test rearing systems throughout trials were set for 2.27 m^3/min to obtain preferential mixing and flow, and to maintain equivalent hydraulic characteristics. Equal flow rates were verified using NaCl as a tracer for each test. To provide the tracer, a stock solution of 60 g/L NaCl, mixed with a power head pump in a 1514 L tank was introduced into the test systems with a double-headed peristaltic pump (Masterflex Model

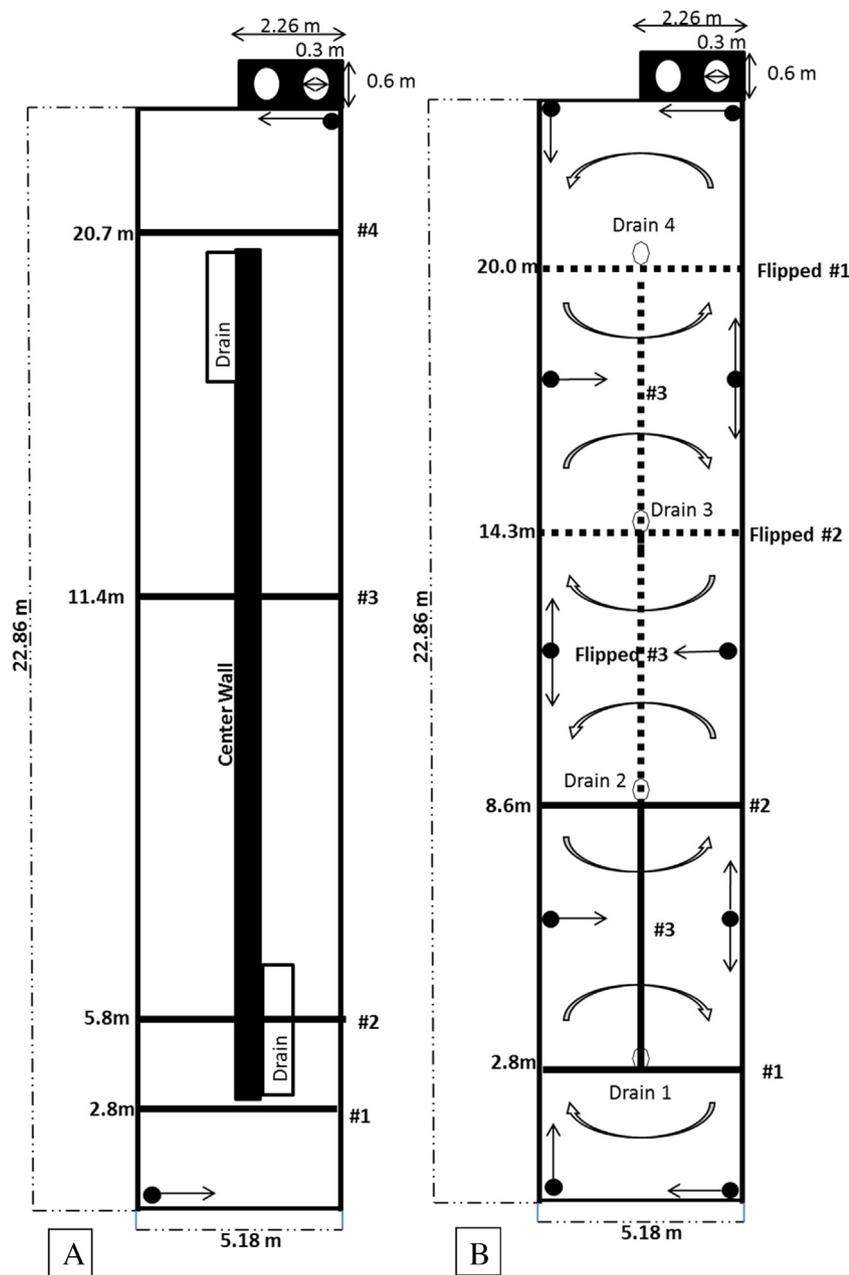


Fig. 1. Schematic of Burrows pond and mixed cell raceway rearing systems evaluated in the studies. The location of inflow and drains, and transects measured for flow and velocity models is diagramed.

Table 1
Summary of estimated biomass and mean total length and mean weight of of Steelhead Trout reared in the mixed cell and Burrows pond during modeling of hydraulics with a NaCl tracer, Dworshak National Fish Hatchery, 2009–2010.

	Mixed cell			Burrows pond		
	Biomass	Mean		Biomass	Mean	
Date and age of fish	(kg)	Total length (mm)	weight(g)	(kg)	Total length (mm)	weight(g)
24-Nov-09 age 0	1071	147	34	1288	156	39
18-Mar-10 yearling	1092	178	58	1172	183	63

7545-30) into valve ports in the inflow pipes with 1.27 cm diameter tygon tubing. The pumping rate was measured by timing the rate of fill or depletion of a known volume.

The conductivity of each test system was measured and recorded with an YSI 556 MPS multiprobe meter (YSI, Inc., Yellow

Springs, Ohio) before and during tests in the effluent standpipe box of each system. The tracer solution was considered fully mixed in the rearing unit when the conductivity of effluent remained consistent for 30 min.

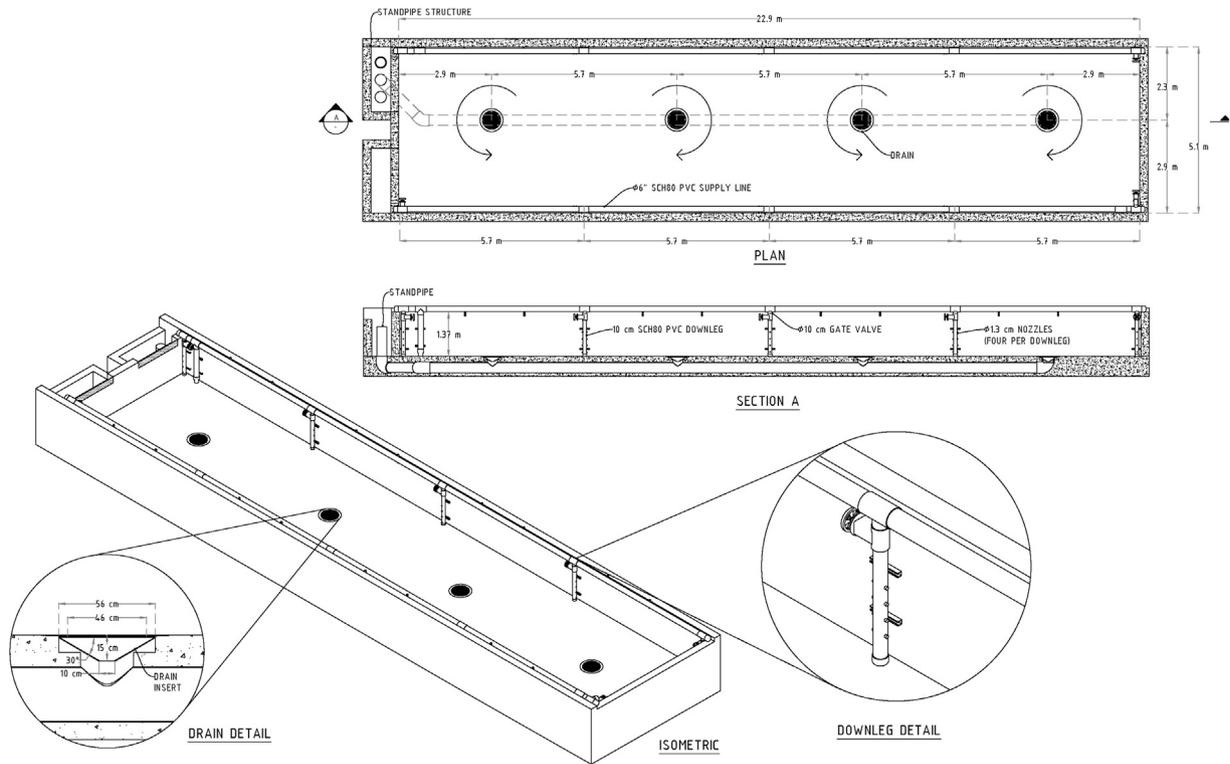


Fig. 2. Plan view, cross section, and isometric profiles of the mixed cell reway, with details of the dimensions of the down-legs, drains and standpipe.

Discharge (Q) in L/min was calculated using the relationship:

$$Q = q \frac{C_1 - C_2}{C_2 - C_0} \quad (1)$$

q = the discharge (L/min) of the concentrated salt solution injected into the flow;

C_0 = the natural or background conductivity (mS/cm);

C_1 = the conductivity (mS/cm) of the concentrated salt solution;

C_2 = the conductivity (mS/cm) in the effluent after full mixing, which includes background conductivity (Haan et al., 1994; BOR, 2001).

Once the salt solution was fully mixed into the MCR or BP and inflow was $2.27 \text{ m}^3/\text{min}$, the valves to the salt ports were closed and the depletion of conductivity was recorded for 4 h to determine the rate of depletion. Depletion curves for the tracer in each trial were modeled using the proportional change in conductivity over time. The change in conductivity was normalized (NC) to a range of 0–1 for each trial by the following equation:

$$NC = \frac{C_i - C_0}{C_{\max} - C_0} = \frac{\Delta C}{\Delta C_{\max}} \quad (2)$$

C_i is conductivity in mS/cm at time i ;

C_0 is natural or background conductivity (mS/cm);

and C_{\max} is the maximum conductivity (mS/cm) or the conductivity before peristaltic pump was shut down.

Chemical engineering reactor equations were used to calculate a series of hydraulic characteristics from the step down analysis of the salt tracer concentration (Levenspiel 1979). They included mean hydraulic residence time (\bar{t}_c Eq. (3)) of water within the rearing units, the variance about the mean hydraulic resi-

dence time (σ^2 Eq. (4)), and variance adjusted hydraulic residence (Eq. (5)).

$$\bar{t}_c = \frac{\sum_{i=1}^n t_i \Delta C_i}{\Delta C_{\max}} \quad (3)$$

$$\sigma^2 = \frac{\sum_{i=1}^n t_i^2 \Delta C_i}{\Delta C_{\max}} - (\bar{t}_c)^2 \quad (4)$$

$$\frac{\sigma^2}{(\bar{t}_c)^2} = 2 \left(\frac{D}{\mu L} \right) - 2 \left(\frac{D}{\mu L} \right)^2 \left[1 - \exp^{-\frac{\mu L}{D}} \right] \quad (5)$$

The mean hydraulic residence time described the time to replace half of the water, and the variance estimated the distribution to explore long depletion times in the data. The axial dispersion number ($\frac{D}{\mu L}$) was used to establish the extent of mixing within the tanks evaluated. A $\frac{D}{\mu L} > 0.01$ indicates a large deviation from ideal plug flow movement toward mixed flow reactor behavior (Levenspiel, 1979).

A theoretical retention time, \bar{t} , was estimated by using the volume of the rearing units divided by the discharge rate. We adjusted the volume of the rearing units for the volume displaced by the biomass of the fish at each trial. The mean hydraulic residence time, \bar{t}_c , was compared to the theoretical hydraulic residence time (\bar{t}) to determine the turnover efficiency, the extent of stagnant regions, SR, and the volume of the stagnant regions, (volume*stagnant regions) as a percentage of volume as follows:

$$SR = 1 - \text{turnover efficiency} = 1 - \bar{t}_c / \bar{t} \quad (6)$$

The turnover efficiency indicated how quickly water particles were removed from the BP and MCR, and stagnant regions were the reciprocal of turnover efficiency.

To estimate a rate of depletion, we transformed the normalized conductivity with a negative natural logarithm and obtained

a linear regression of these values with time. We compared the slopes of the different regressions with analysis of covariance, and used single degree of freedom comparisons to determine significant differences between trials. All statistical analyses were conducted using SAS 9.3 (SAS Institute, Cary, NC).

2.3. Directional velocity profile

To provide a profile of the directional velocity in each rearing unit, we recorded velocity profiles before fish were introduced using a SonTek Argonaut-Acoustic Doppler Velocimeter (SonTek/YSI, San Diego, CA). The instrument measurement precision was within 0.001–6 m/s with a resolution of ± 0.0001 and accuracy of $\pm 1\%$ of measured velocity. Measurements in each direction (x, y, z) were made every 0.305 m across horizontal transects established in each rearing unit, and at two depths: 0.305 and 0.610 m. At each reading, velocities and speeds were recorded over an eight min period, with the instrument reporting averages each 15 s. These 15 s averages were averaged together to calculate the average velocity or speed for that transect at each point and depth measured.

Velocities in the BP were recorded along two transects, each 2.16 m from both end walls (transects 1 and 4; Fig. 1A), 5.817 m from end wall over first drain (transect 2; Fig. 1A), and in the middle of the pond at 11.43 m (transect 3; Fig. 1A). The horizontal locations of transects in the MCR were: 2.8 m from the end wall and 0.254 m from the first drain (transect 1; Fig. 1B); 8.6 m from the end wall and 0.254 m from the second drain (transect 2; Fig. 1B). An additional transect was measured at 90° from the center of drain 1 to the center of drain 2 between the two vertical cross sections (transect 3; Fig. 1B).

Measurements from transects in the MCR were transposed and duplicated (Fig. 1) in a similar fashion as Labatut et al. (2007) to provide a model for the complete rearing unit, and data were plotted with contour and vector plots (Systat Software, Inc., San Jose, CA.). We also measured velocities along one cross section at 0.61 m in the BP and 0.305 m in the MCR during the particle removal studies to verify that flow characteristics were similar. Average velocities were compared with paired *t*-tests.

2.4. Particle removal

To evaluate the removal of small particles similar to trout fecal material and/or small invasive mollusks such as NZMS, we diverted effluent from drains in the BP and MCR to an adjacent BP for evaluation. To capture the effluent, we plugged each drain with inflatable pipe plugs, and modified the perforations of the drain screens to accommodate a 5.1 cm-diameter fitting in the center. A 5.1 cm-diameter PVC pipe was then attached about 5.1 cm below the drain screen and configured up out of the unit. To remove water from the plugged drains, we used trash pumps (Gasoline EPT3 Tsurumi Pump, Glendale Heights, IL) calibrated to provide 568 L/min each for a total of 2272 L/min to match the input flow. All effluent was filtered through 80 μm mesh plankton nets, 30 cm diameter by 90 cm long. We rotated several nets to process the contents of each cod end over time. We placed a 100 μm mesh plankton tow net with the bottom stitched together inside the standpipe emerging from each rearing system to capture any particles that may not have been captured by the effluent diversion.

The particles tested were sinking, cylindrical acrylonitrile butadiene styrene (ABS) beads, 3 mm long and 3 mm outside diameter with a specific gravity of 1.05 (Summerfelt and Timmons, 2000). Replicated tests of particle removal efficiency were conducted during June 2010 at design flows of 2271 L/min after fish were released from the rearing systems. For each trial of removal efficiency, a

known quantity of beads (dry weight) was hydrated. For the first two trials of the MCR, 4535 g of beads were introduced in a manner as if we were scattering feed particles, placing approximately 1134 g into each cell, over 1 min. For the third trial, we increased the weight of beads introduced (12,600 g) into the MCR, 3150 g into each cell. Beads were collected from the pumped effluent with plankton nets at intervals of 2.5, 6, 10, 15, and 20 min for trials 1 and 2, and then at intervals of 1, 5, 10, 15, and 20 min for trial 3. For each test in the BP, 4535 g of beads were distributed from the center wall over the entire length of the BP over 1 min. Beads were collected at 2.5 min intervals until 10 min, 5 min intervals until 20 min and then 10 min intervals until 50 min had elapsed. The beads collected from each sampling interval and trial were stored separately and were later dried and weighed to evaluate the cumulative mass removal by each time interval.

2.4.1. Data modeling and analysis

We calculated a mean and variance of hydraulic residence time of the particles. The pulse response data were analyzed with the mixing cup method with “sloppy” input of tracer (Levenspiel, 1979).

$$\bar{t}_c = \frac{\sum_{i=1}^n t_i \Delta t_i C_i}{\Delta t_i C_i} / (\text{output/input}) \quad (7)$$

$$\sigma^2 = \left(\frac{\sum_{i=1}^n t_i^2 \Delta t_i C_i}{\sum_{i=1}^n \Delta t_i C_i} - (\bar{t}_c)^2 \right) / (\text{output/input}) \quad (8)$$

The rate that the beads were flushed from the drains, *k*, was calculated using the following equation (Summerfelt and Timmons, 2000):

$$\text{percent flushing due to enrichment} = \frac{k}{k + \frac{Q}{V}} \times 100 \quad (9)$$

where *k* can also be found by plotting the negative natural log of the fraction of solids remaining versus time where (*Q/V* + *k*) is equal to the slope parameter.

3. Results

3.1. Computational fluid dynamics

CFD runs demonstrated the ability of the BP retrofit to establish counter rotating cells with velocities and vectors expected to purge settleable solids. Jet wake on the long axis of each cell tended to rise toward the surface while jet wakes associated with the short axis tended to drop and encourage the cell to cell exchange observed by Watten et al. (2000) at a smaller scale. Vortices linked to individual cell drains at the surface were established along the longitudinal centerline of the vessel while the apex of the vortex angled from the surface position to the screened surface of the drain. Down leg piping produced local low velocity regions. Use of the existing drain below grade and linked to the displaced centerline of individual cell drain plates reduced the mean velocity near the floor by 2.2% when compared to the centered drain position, i.e., at a flow rate of 2.27 m³/min and with a working depth of 0.91 m predicted velocities were 9.65 cm/s versus 9.44 cm/s. Under these same operating conditions, and with the off center drain configuration, the mean velocity increased from 9.5 cm/s near the floor to 10.4 cm/s at mid depth demonstrating that velocities were lower along the tank floor than at the tank surface. Tank water depth had little effect on mean velocity when operating at a flow rate of 2.27 m³/min; at the floor and mid depth sampling planes, velocities were 9.44 and 10.4 cm/s at 0.91 m and 9.42 and 10.57 cm/s at 0.79 m, respectively. Mean velocities were sensitive to changes in flow rate dropping from 9.44 cm/s to 7.86 cm/s as flow

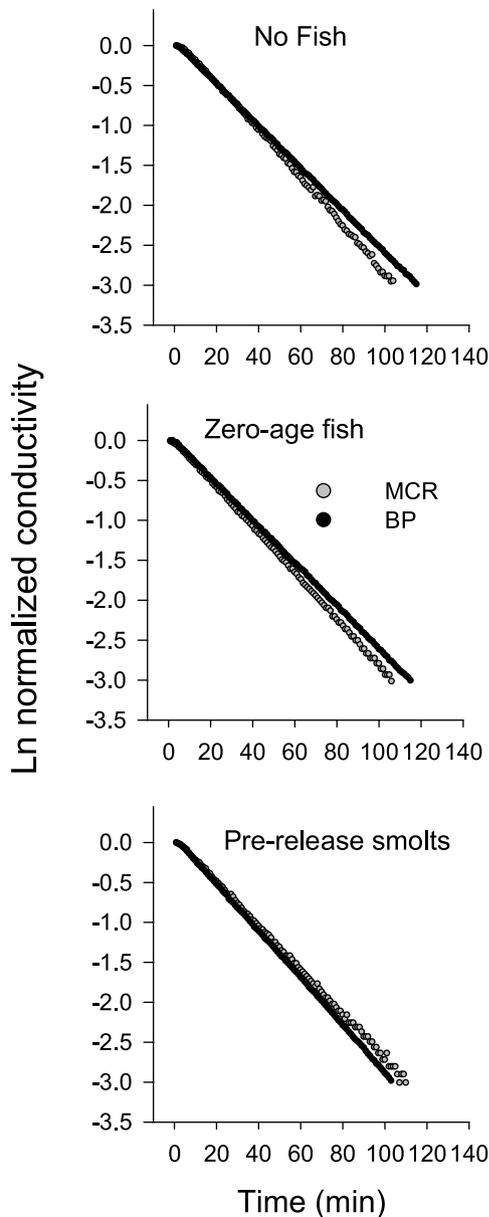


Fig. 3. Linear models of ln-normalized conductivity versus time for mixed cell raceway (MCR) and Burrows pond (BP) measured at three times, two of which were with fish.

was reduced from 2.27 to 1.89 m³/min. Water depth was fixed at 0.91 m.

3.2. Hydraulic characteristics using tracer

To eliminate the bias associated with fluctuations in the conductivity measurements, we truncated our depletion data, removing the last 5% of all measures in the tail of distribution at low levels and thus report the 95% depletion (Table 2). When the systems were without fish or with 0-age fish, depletion of the tracer was about 10 min slower in the BP than in the MCR. Mean residence time for all units was lower than the theoretical hydraulic residence time of approximately 50 min (Table 2). In the MCR, the time to depletion of tracer increased with size of fish, and in the BP the estimated time to depletion was shortest with pre-release smolts (Fig. 3). We found significant differences among the slopes of regressions fit to the ln-transformed normalized conductivity ($F = 48,103$; $P < 0.0001$). Multiple comparisons among slopes

showed the presence of larger fish the slope of the depletion of salt tracer in the BP ($P < 0.05$).

From these measures, we estimated that the proportion of stagnant regions was similar between the two systems (about 22%; Table 2). Variance was higher in measures in the BP with no fish and 0-age fish, but reversed in March with the pre-release smolts. The calculated dispersion factor supported considerable mixing in both systems, and large variances indicated large amount of dispersion and mixing.

3.3. Directional velocity profile

The MCR had higher mean velocities and more uniform velocity distributions compared to the BP (Figs. 4 and 5). Mean velocities were 0.234 m/s for the MCR and 0.168 m/s for the BP. The velocities measured at the two depths were not significantly different ($P > 0.05$). Velocity profiles of the MCR were consistent with the CFD models with lower velocity occurring toward the bottom. The contour and vector plots illustrate clearly the areas around the drains of the mixed cell that had slower velocity, and the areas near the walls with the fastest velocity. In the BP, all velocities were low, and many areas were 0.2 m/sec and lower (dark green and blue, Fig. 5). The highest velocity was observed nearest to the water jets, and water flow in the BP was mostly in one direction, away from the jets and toward the drains.

3.4. Small particle removal efficiencies

We found no significant differences between the velocities during normal operations tested with salt tracer and those measured during trials with drains plugged and effluent removed with trash pumps (Tables 2 and 3). Thus, we were able to model empirical and theoretical data to determine the hydraulic characteristics of the small particles (beads) following introduction into the rearing units. In the MCR, 88.6% of the beads introduced into the system were recovered in the plankton nets, compared with a mean of only 8% for the BP. The mean hydraulic residence time for the beads was 12.2 min in the MCR versus estimates of more than 273 min in the BP. The beads in the mixed cell were removed 4 times faster than the water particle removal rate estimated with the salt tracer (12.2 min compared to the theoretical residence time of 47.6 min). However, water in the BP moved out of the system at two to ten times faster than did the beads, which indicated that the beads were not carried out by the water.

The rate of removal associated with the force of the MCR drains corresponded to an average of 90.7% of the beads being removed by the forces of the drain. The removal of the beads from the drain of the MCR fit a first order kinetics model, and percent flushing due to enrichment determined how much of the removal was associated with the mass action of the water flow (V/Q) versus the enrichment of the beads. In the BP, the estimate of flushing rate k was so low that only beads that were transported out of the system with the water column were collected, and most of the beads settled before being flushed down the drain.

4. Discussion

Our study provides the first assessment of a large MCR in a side-by-side field comparison with BP with and without fish. In addition, we evaluated the hydraulic characteristics with two sizes of fish. The modification of two BP into two MCR systems was undertaken as a research effort by hatchery managers at the Dworshak National Fish Hatchery, Idaho, to determine if personnel costs for pond cleaning could be reduced, fish health and performance could be improved and the overall fish rearing environment could be improved by improvements in water quality. The Dworshak

Table 2
Hydraulic characteristics of the mixed cell raceway and Burrows pond at three time periods, two of which were with Steelhead Trout (see Table 1). Rearing volume adjustments were made for fish loading, and discharge was measured at effluent standpipe. Hydraulic measurements were made in September before fish were placed into the systems, and then at two times during rearing (November and March). Calculations were made using Eq. (3) through (6). The slopes of the linear regression of the negative natural log of the normalized conductivity were compared and superscripted values with the same common letters did not differ ($P > 0.05$).

	Mixed cell			Burrows pond		
	Sept No Fish	Nov 0-age fish	Mar Pre-release smolts	Sept No fish	Nov 0-age fish	Mar Pre-release smolts
Volume (L)	116,210	115,139	115,118	113,800	112,510	116,842
Discharge (L/min)	2271	2315	2277	2234	2240	2427
95% depletion of tracer (min)	104	105	107	115	115	103
Theoretical residence \bar{t} (min)	51.17	49.74	50.56	50.94	50.23	48.14
Mean hydraulic residence \bar{t}_c (min)	38.58	37.74	38.97	40.42	40.73	36.99
Variance σ^2 (min)	76.63	103.42	178.14	173.49	161.62	129.02
Variance adjusted hydraulic residence σ^2/\bar{t}_c^2	0.05	0.07	0.12	0.11	0.10	0.09
Mixing rate $D/\mu\text{L}$	0.03	0.04	0.06	0.06	0.06	0.05
Proportion stagnant region SR	0.25	0.24	0.23	0.20	0.19	0.23
Regression slope normalized conductivity	0.0296 ^b	0.0288 ^b	0.0276 ^c	0.0264 ^d	0.0267 ^d	0.0294 ^e

Table 3
Hydraulic characteristics of the mixed cell raceway and Burrows pond during repeated trials of particle (beads) removal conducted after fish were released from rearing systems. Calculations were made using Eqs. (7) through (9). The volume of each rearing unit during trials was maintained at 108,160 L and 103,168 L for the mixed cell and Burrows pond, respectively. * indicates parameters that were not estimable due to poor removal of particles from the system.

	Mixed cell				Burrows pond		
	Trial 1	Trial 2	Trial 3	Mean (SE)	Trial 1	Trial 2	Mean (SE)
Theoretical residence \bar{t} (min)	47.6	47.6	47.6	47.6	46.0	46.0	46.0
Percent particles collected	97.3	97.7	70.8	88.6 (15)	6.0	9.9	8.0 (2.8)
Flushing rate k/min	0.42	0.15	0.17	0.25 (0.15)	*	*	*
Percent flushing due to enrichment	95.3	87.9	89.0	90.7 (3.98)	*	*	*
Mean hydraulic residence \bar{t}_c (min)	16.7	10.1	9.9	12.2 (3.9)	452.8	94.5	273.7 (253.4)
Variance σ^2 (min)	263.0	163.8	152.6	193.14 (60.8)	5614.1	3689.9	4652.0 (1360.6)

National Fish Hatchery, Idaho, rears about 2 million Steelhead Trout *Oncorhynchus mykiss* annually that are released as smolts as part of a U.S. Army Corps of Engineers dam mitigation program. Fish are produced in 84 replicate Burrow's type ponds measuring 22.86 by 5.18 m. Poor hydraulic conditions allow for inactive regions that, in turn, allow for the accumulation of waste solids. Modifications of the suite of BP were proposed as the least cost. In addition, the MCR system was proposed to improve bio-security measures to reduce transporting invasive species in the feces of fish (Bruce and Moffitt, 2010). Additional modifications of the design could have been made to separate the solid waste particles into a separate stream, but were not part of this study.

Our analysis of the fluid responses in the two systems using a salt tracer showed both systems had measured mean water particle residence times that were lower than theoretical estimates. The variances around these measures were high. In the MCR, the fish effect could be observed to increase the variance, but fish reduced the variance in the BP (Table 2). The depletion of tracer was nearly 10 min faster in the MCR over the BP when no fish or small fish were present. Studies by Rasmussen et al. (2005) reported increased mean residence time ratios when fish were present and at two flow rates. Our studies found similar or lower mean hydraulic residence times occurred with fish in the rearing systems. Mixing rate in our studies increased with fish in the MCR, but decreased somewhat with larger fish in the BP. Rasmussen et al. (2005) reported decreases in mixing with fish at both flow rates they tested. Clearly the size and density of fish in the system can affect the hydraulic characteristics, and should be considered in system design and operation. Our measures of tracer were all at the outflow, but Rasmussen et al. (2005) measured both outlet-based and in-tank dispersion.

Differences in hydrodynamics between the BP and MCR became most clear during evaluations of small particle removal compared

with the depletion of water particles. We recovered only 8% of the 3 mm beads introduced into the BP, but over 88% of all beads introduced into the MCR were recovered. The differences in velocity between the two systems was pronounced, and most of the BP velocities were less than 0.15 m/sec (Figs. 4 and 5). This velocity gradient was not sufficient to move the particles introduced into the system during the trials. The more complete and efficient small particle removal in the MCR demonstrated that waste feed and feces were quickly flushed from the rearing vessel, reducing the possibility of water quality degradation from solids breakup and nutrient leaching in stagnant areas. Moreover, rapid removal of solids reduced the reservoirs for bacterial and viral pathogens associated with solids and feces (Wold et al., 2014). Our tests did not evaluate a range of particles as did Labatut et al. (2015) who simulated the residence time for particles from 1 μ to 3000 μm over a 36 min period in a similar sized three-cell MCR. Their simulations used particles of the similar specific gravity as our trials, (around 1.05). Labatut et al. (2015) estimated that only 5% of the smallest particles would be removed, and ~ 50% of particles 10 μm would be removed. They estimated nearly all the particles 100 μm would be removed. Our empirical tests with 3-mm particles observed a lower mean residence time (12.2 min vs. 6.9 min) than times simulated by Labatut et al. (2015).

The hydraulic tests were conducted in a field trial setting and hatchery staff controlled the flow, feed, and fish during the studies. During the length of the rearing program, the hatchery staff observed changes in the flows in the units thus affecting the hydraulics. However, before any of our measurements and observations of fish behavior, we adjusted flows to be as designed. The Steelhead Trout observed in the MCR aligned with the direction of flows and were distributed throughout the circular current and the individual cells. Fish were observed swimming in and out of the vortex of each cell. In contrast, fish in the BP congregated around

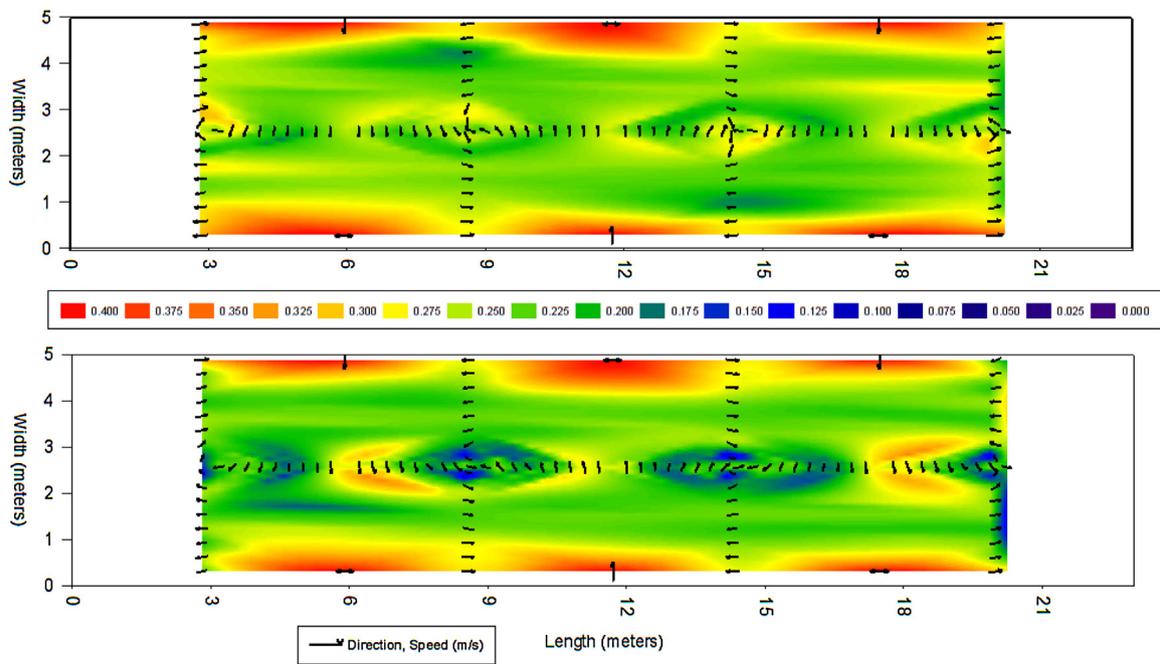


Fig. 4. Velocity contours (m/s) and vector plots at 0.305 m from surface (top plot) and 0.610 m from surface (bottom plot) in the mixed cell raceway system.

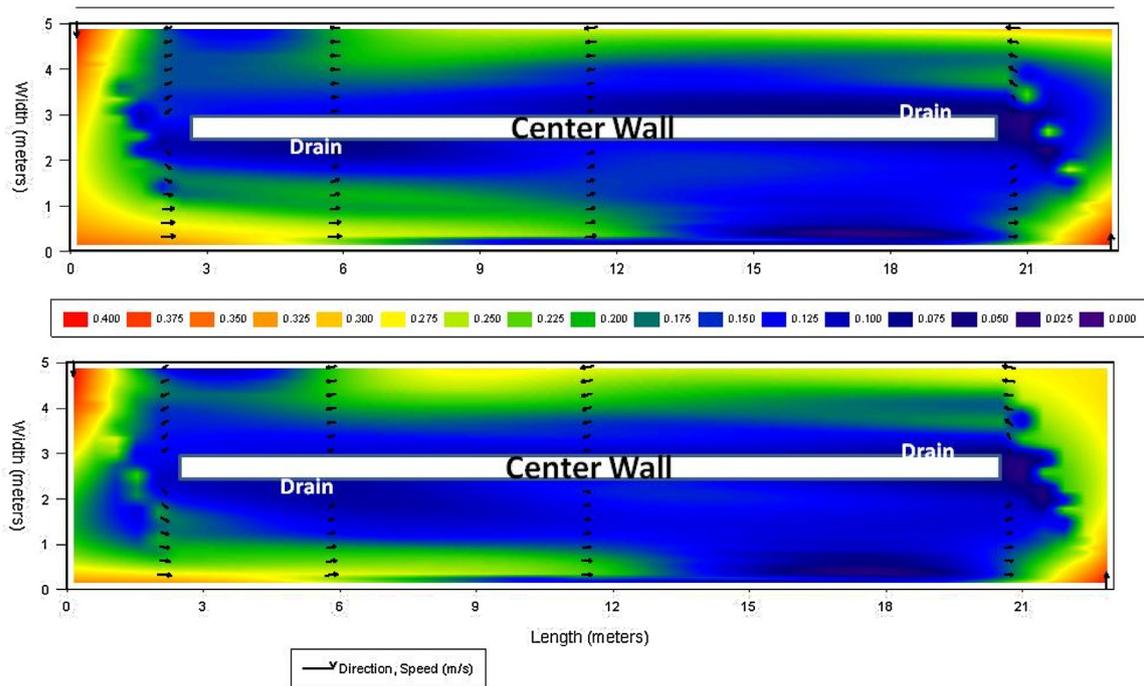


Fig. 5. Velocity contours (m/s) and vector plots measured at 0.305 m from the surface (top) and 0.610 m from the surface (bottom) in the Burrows pond system.

the inlet jets and in areas of highest velocity. Watten et al. (2000) suggested swimming behavior required by fish in the MCR should condition fish and increase white mussel aerobic scope, improve cardiac output, and enhance oxygen carrying capacity in the blood. Recent physiological studies and reviews of conservation hatchery operations support that opportunities for exercise can result in higher growth rates, muscle mass development, reduced aggression, and increased survival (Flagg and Nash, 1999; Ibarz et al., 2011; Palstra and Planas, 2011; Palstra et al., 2015).

The MCR design provides higher velocities and high dispersion that can remove waste particles, lowering the risk of disease and the amount of physical cleaning needed by hatchery personnel. The presence of fish in MCR increased mixing of water particles, and we propose that the MCR could be a tool to deplete fish prior to release, removing fecal particles that might contain invasive NZMS or other small invasive invertebrates from the water column. The high velocities and the low particle residence times of the MCR support such a strategy. Haynes et al. (1985) demonstrated that NZMS could remain in place at velocities of 30 cm/s.

In conclusion, our studies provide strong support for positive outcome from retro-fitting BP rearing systems into MCR. Additional studies are recommended to document the operational costs and management challenges of operations, as well as studies of fish health, physiology, and survival in the rearing environment. Further comparisons could include studies of return rates of adults following ocean rearing over several years of production.

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