Aquaculture 326–329 (2012) 156–162

Contents lists available at SciVerse ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Hydrocyclonic separation of invasive New Zealand mudsnails from an aquaculture water source

R. Jordan Nielson [a], Christine M. Moffitt [a,b,*], Barnaby J. Watten [c]

[a] Idaho Cooperative Fish and Wildlife Research Unit, USA
[b] U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, ID 83844-1141, USA
[c] U.S. Geological Survey, Conte Anadromous Fish Research Laboratory, Turners Falls, MA 01376, USA

ARTICLE INFO

Article history:
Received 22 April 2011
Received in revised form 20 November 2011
Accepted 21 November 2011
Available online 26 November 2011

Keywords:
Aquatic invasive species
Water filtration
New Zealand mudsnails
Hydrocyclone

ABSTRACT

Invasive New Zealand mudsnails (*Potamopyrgus antipodarum*, NZMS) have infested freshwater aquaculture facilities in the western United States and disrupted stocking or fish transportation activities because of the risk of transporting NZMS to naïve locations. We tested the efficacy of a gravity-fed, hydrocyclonic separation system to remove NZMS from an aquaculture water source at two design flows: 367 L/min and 257 L/min. The hydrocyclone effectively filtered all sizes of snails (including newly emerged neonates) from inflows. We modeled cumulative recovery of three sizes of snails, and determined that both juvenile and adult sized snails were transported similarly through the filtration system, but the transit of neonates was faster and similar to the transport of water particles. We found that transit times through the filtration system were different between the two flows regardless of snail size, and the hydrocyclone filter operated more as a plug flow system with dispersion, especially when transporting and removing the larger sized adult and juvenile sized snails. Our study supports hydrocyclonic filtration as an important tool to provide snail free water for aquaculture operations that require uninfested water sources.

Published by Elsevier B.V.

1. Introduction

New Zealand mudsnails (*Potamopyrgus antipodarum*, NZMS) are native to both fresh and brackish water of New Zealand and its surrounding islands (Gerard and Lannic, 2003), but have invaded waters in Australia (Ponder, 1988), Europe (Bondesen and Kaiser, 1949) and the United States (Cross et al., 2010). In the U.S., the reported detection of NZMS was in benthos sampled in the Nature Conservancy's Thousand Springs Preserve near Hagerman, Idaho (Bowler, 1991). The NZMS are now found in British Columbia, every state in the Western U.S. except New Mexico, in the Great Lakes, Wisconsin and Minnesota (Bersine et al., 2008; Cross et al., 2010; Davidson et al., 2008; Dybdahl and Drown, 2011; Grigorovich et al., 2003; Levri et al., 2008; Zaranko et al., 1997).

New Zealand mudsnails reproduce both sexually and asexually via parthenogenesis (Winterbourn, 1970), but populations in the U.S. are primarily composed of asexually reproducing females (Dybdahl and Drown, 2011; Wallace, 1992). A single snail can produce up to 120 embryos (Alonso and Castro-Díez 2008; Richards et al., 2004; Schreiber et al., 1998), and thereby introduce a new population into a naïve water body. When populations reach high densities in freshwater, they have been reported to disrupt the function of the native ecosystem (Arango et al., 2009; Hall et al., 2006), although their influence may not be as severe in brackish water communities (Brenneis et al., 2010).

Fish stocking, fishing, and recreational boating have been key factors associated with world wide dispersal of NZMS (Alonso and Castro-Díez 2008; Bruce and Moffitt, 2010; Loo et al. 2007). Fish or transport water from infested hatcheries can spread NZMS to uninfested water bodies, since snails are consumed by fish and can pass through the intestinal tract of a fish unharmed (Bondesen and Kaiser, 1949; Bruce et al., 2009; Haynes et al., 1985). In addition, the use of biocides to remove pests and clean springs is often not feasible due to regulatory requirements, and risks to other biota of special concern such as threatened or endangered species. Because of these risks, infestations of NZMS in hatcheries that routinely transport fish to other locations for mitigation, conservation, recreation, and/or supplementation have caused concern with managers and conservationists. To ensure that NZMS are not transported with fish from an infested aquaculture facility, there is a need for adequate NZMS free water to provide an extended depuration of infested fish before transportation (Bruce and Moffitt, 2010).

Cyclonic separation is used in many industries to separate particulate wastes from air and water. Hydrocyclone filtration uses pressurized water and centrifugal force to remove particles of a higher specific gravity than water (Kraipech et al., 2006), and filtration can be relatively low cost compared with other treatment methods

* Corresponding author at: U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, Idaho 83844-1141, USA. Tel./fax: +1 208 885 7047.
E-mail address: cmoffitt@uidaho.edu (C.M. Moffitt).

0044-8486/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.aquaculture.2011.11.035

especially those with moving parts (Ortega-Rivas, 2004; Williams and Evans, 2007). Hydrocyclones are used extensively in mining (Trawinski, 1976) and in the food industry (Ortega-Rivas, 2004). Hydrocyclones are used as a first step to remove particles in ballast waters (Wang and Wang, 2009); and recently trials have been conducted to evaluate their efficacy to remove invasive species with mixed success (Abu-Khader et al., 2011; Kurtela and Komadina, 2010; Parsons and Harkins, 2002). We know of no study using this tool to clean water sources in fish hatcheries.

The objectives of this study were: 1) to test the efficacy and filtration efficiency of a hydrocyclone system to remove all life stages of New Zealand mudsnails from inflow waters; and 2) to model and compare the transit properties of water and snail particles through the filtration system.

2. Methods

2.1. Location, design, and instrumentation

This study was conducted at the Hagerman National Fish Hatchery, Hagerman, Idaho during the summer and fall of 2007, and the spring of 2008. Water temperature for all trials was constant and averaged 15 °C. The test hydrocyclone was 15.25 cm diameter (Krebs model U6-gMAX; FLSmidth Krebs, Tucson, Arizona). Two vortex finder apertures were designed and tested for each of the two test flow rates: 5.7 cm (367 L/min) or 3.8 cm (257 L/min). The apex opening for both trials was 1.27 cm and allowed approximately 13.4 L/min to the underflow (Fig. 1). Design pressure for hydrocyclone operation was 69 kPa for both flow rates.

The hydrocyclone water intake was placed in Len Lewis spring on the northeast side of the hatchery. The hydrocyclone filter was placed

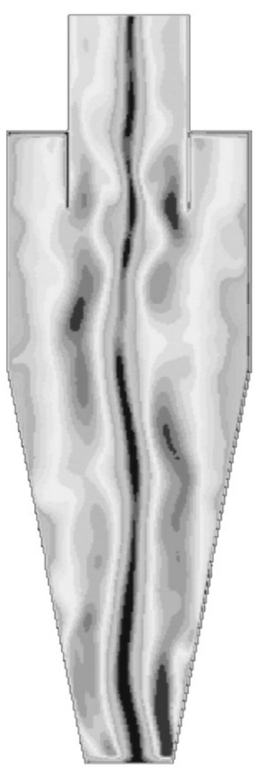

Fig. 1. Computational Fluid Dynamic (CFD) image of tangential velocities in a hydrocyclone (Courtesy of FLSmidth Krebs, http://www.krebsengineers.com/documents/71_gmax_development-coal-09-30-02.pdf). The darker colors indicate highest velocities. The tangential flow process enhances centrifugal forces to move solid particles outwards, and downwards in a spiral path into an underflow. The filtered water moves upwards to the center of the spiral, toward the top outlet (darkest color center).

next to the Main Spring head box supplying water to the hatchery, providing a 9.1 m drop from the water intake to the hydrocyclone and head pressure (69 kPa) for efficient operation of the hydrocyclone (Fig. 2).

The water intake for the hydrocyclone was in a bucket placed tangential to the spring flow to limit fouling. The center of the bucket was modified to accept a PVC pipe (7.6 cm diameter) that ran from the spring along a road for 12 m. The PVC pipe was attached to a 7.6 cm diameter, flexible hose for a distance of 72 m to the filtration site (Fig. 2). We mounted the hose to a PVC 7.6 cm diameter pipe at the filter. We monitored instantaneous flow (L/min) and totalized flow over operations with a flow totalizer (Signet 8150; George Fisher Signet, Inc., El Monte, California). Source water was filtered by the hydrocyclone into two water streams: the overflow or clean water, and the underflow or filtrate. The underflow was constricted by design to achieve a flow of approximately 13.44 L/min, and the overflow (353 or 243 L/min, depending on head fitting) was directed into a 7.6 cm diameter pipe manifold outfitted with 4 gate valves to direct water into ring nets (80 μm mesh, 30.5 cm diameter) suspended over two 104 L collection basins. The underflow was filtered with one net of the same size attached below the cone. The basin overflows were directed back to the spring water supply serving the hatchery. Water flow and pressures were adjusted with gate valves on the inlet and outlet of the hydrocyclone.

2.2. Snail filtration and transit

Snails for tests were collected from Len Lewis Spring at the hatchery, and separated into three sizes: adults (>2 mm); juveniles (1 mm to 2 mm); and neonates (<1 mm). We obtained the neonates by retaining adult snails in containers at room temperature (22 °C) for 24–48 h, and removing newly emerged neonates with the aid of a microscope using a pipette and spatula. The neonate NZMS were dyed with 5% Rose Bengal (Sigma-Aldrich Co., Dallas, Texas) to improve visibility and identification in evaluations. Samples of 100 adults, 50 juveniles, or 50 neonate snails were counted into 120 cm^3 plastic cups 1–2 days prior to a trial and refrigerated until use (5 °C).

We began each test of transit and filtration with introduction of 100 adult, 50 juvenile, or 50 neonate snails over 60 s into a port at the upstream water intake of the hydrocyclone. We filtered water from the underflow and overflow of the hydrocyclone (Fig. 2), and removed and replaced nets at pre-selected time intervals at the overflow ports based on flow rates and snail sizes (Table 1). We collected filtrate from the nets by rinsing the contents with clean water down into the cod end. Contents from each cod end were placed into containers and fixed in 10% buffered formalin for at least 24 h, and then rinsed and transferred into 40% 2-propanol for storage. Using a dissecting microscope, we enumerated the number, size, and condition of all snails collected at each time interval. A subset of 10% of samples was recounted for quality control.

2.3. Water transit

We introduced NaCl as a conservative tracer to model water movement through the hydrocyclone at each test flow (257 and 367 L/min). Conductivity was recorded at 1 s intervals with a recording YSI 556 MPS multi-probe meter (YSI, Inc., Yellow Springs, Ohio) with the probe positioned in a 4 L container receiving the hydrocyclone underflow. The measurements of salinity and conductivity were used to estimate residence time distribution (RTD; Danckwerts, 1953; Levenspiel, 1984). We used RTD to verify the filtration time needed for collecting snails and modeling snail transit through the hydrocyclone. We used both a pulse and step-down approach (Danckwerts, 1953) for analysis: step-down trials were used to evaluate RTD of the overflow, and pulse trials were used to establish, concurrently, the RTD of the overflow and underflow.

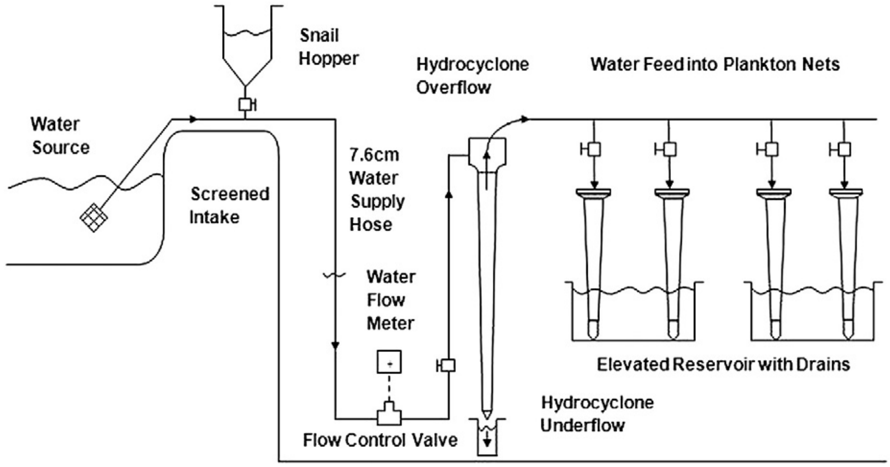

Fig. 2. Scaled schematic diagram of the test hydrocyclone with photos of sample release hopper at intake and filtration testing system at the hatchery.

2.3.1. Step-down trials

A concentrated solution of NaCl was introduced into the hydrocyclone at approximately 20 L/min for a period of time sufficient to adjust the conductivity of the hydrocyclone underflow to an elevated and stable conductivity level for at least 1 min. To achieve a step down in tracer concentration, the flow of tracer solution was then abruptly terminated and the decay in concentration was monitored via changes in conductivity. Each set of test conditions was replicated 4 times.

2.3.2. Pulse trials

A concentrated NaCl solution was introduced as a tracer into the hydrocyclone water supply line at a rate of 0.33 L/s for a period of 1 min. Grab samples were taken every 10 s from both the overflow and underflow starting at 60 s for flows at 367 L/min; and starting at 80 s for flows at 257 L/min, and conductivity measured. The conductivity of water exiting the hydrocyclone at the underflow was recorded before each trial and used as baseline conductivity. Each set of test conditions was replicated 2 times.

2.4. Statistical analyses

2.4.1. Snail transit

Recovery efficiency was determined by comparing the number of NZMS collected at the underflow vs. the number introduced into the system, and expressing the value as a proportion. To compare the transit of the three snail sizes at both test flows, the proportion of snails recovered at each time interval was normalized by calculating the proportion of snails recovered at each time interval (ΔR) by the total number of snails recovered during that trial ($\Delta R/\Delta R_{max}$). The cumulative normalized percentages were graphed and a four parameter logistic curve was fit to each data set. The model for the curves was,

$$y = \min + \left((\max\text{–}\min)/\left(1 + (x/EC50)^{\text{Hillslope}}\right)\right), \tag{1}$$

where y was the percent recovery; ; max was the highest observed value; min was the lowest observed value; x was the elapsed time of the trial; EC50 represented the time to 50% recovery; Hillslope was the greatest absolute value of the slope of the curve. Logistic curves for each of the snail sizes were compared to logistic curves for pulse tracer trials to verify that collection intervals were appropriate for snail trials.

Parameter estimates from logistic curves were compared with a multivariate model (Proc MANOVA; SAS Institute) using the model: $X_{lkr} = \mu + \tau_l + \beta_k + \gamma_{lk} + \varepsilon_{lkr}$, where μ is an overall mean; τ_l was the flow effect; β_k was the size effect; γ_{lk} was the flow/size interaction; and ε_{lkr} is the random error. If an effect was determined significant ($P<0.05$) then individual parameter estimates were compared with ANOVA models using the linear model: $y_i = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk}$, where i was flow; j was snail size; k was replicate; and τ_i, β_j, and $(\tau\beta)_{ij}$ represented the effects of flow, size, and the flow–size interaction respectively. When parameter estimates were significantly different, a Tukey test was used to separate the combined flow X size groups.

Table 1
Intervals used for sampling from the hydrocyclone underflow with plankton nets to model transit of NZMS by size and test flows.

Time interval (s)					
367 L/min			257 L/min		
Adult	Juvenile	Neonate	Adult	Juvenile	Neonate
60	60	60	120	120	90
75	75	75	135	135	105
90	90	90	150	150	120
105	105	105	165	165	135
120	120	120	180	180	150
150	150	150	210	210	165
180	180	180	240	240	180

2.4.2. Water transit

For step-down RTD trials, conductivity measurements were normalized to a proportion of the maximum conductivity value ($\Delta C/\Delta C_{max}$)(Watten et al., 2000). Mean residence time ($\bar{t}$) and variance (σ^2) for each step-down trial were calculated using the equations (Levenspiel, 1984):

$$\bar{t} = \frac{\sum t_i C_i}{\sum C_i} \tag{2}$$

$$\sigma^2 = \frac{\sum t_i^2 C_i}{\sum C_i} - \bar{t}^2 \tag{3}$$

where t_i represents the 1 s time intervals; and C_i represents the corresponding (normalized) conductivity measurement (Levenspiel, 1984). The vessel dispersion number ($D/\mu L$) was then calculated to characterize the amount of mixing or deviation from a plug flow type contacting pattern using $\bar{t}$ and σ^2 and the model (Levenspiel, 1984):

$$\sigma^2/\bar{t}^2 = 2(D/\mu L) - 2(D/\mu L)^2[1 - e^{\mu L/D}]. \quad (4)$$

For pulse RTD trials conductivity measurements were normalized to a percent of the maximum conductivity value ($\Delta C/\Delta C_{max}$) (Watten et al., 2000) and plotted as a normalized cumulative percent conductivity across time. A four-parameter logistic curve was fit to the cumulative conductivity points for comparison to the depletion pattern of snails.

3. Results

3.1. Snail transit

The hydrocyclone was efficient in recovering all three sizes of snails in the underflow, and providing uninfested overflows. We recovered 99.3% of adults, 95% of juveniles, and 69% of neonates that were introduced into the system. Since snails were not recovered from the overflow, and filtration effectiveness was considered to be complete. We recovered shell fragments and fragments of dyed tissues from the nets that substantiated our conclusion that portions of the snails introduced into the hydrocyclone were destroyed by the abrasion within the system, especially the small neonates.

The transit of NZMS through the system increased at the higher flow rate (Fig. 3). Neonate NZMS were transported faster than adult or juvenile sized snails, but we found no significant differences in transit time or pattern between adult or juvenile snails within each test flow (Fig. 3). Each recovery profile provided a significant fit to a four-parameter logistic curve model of the cumulative percent recovery. Our model parameter estimates tested in multivariate models were significantly different for flow and snail size ($P<0.001$; Table 2). When we analyzed the individual model parameter estimates separately, the EC50 and hillslope parameters were significantly different between flows ($P<0.001$) and snail size ($P=0.0025$, Table 3). Within each flow rate, hillslope and EC50 for adult and juveniles did not differ, but model parameters were different for neonates (Fig. 4).

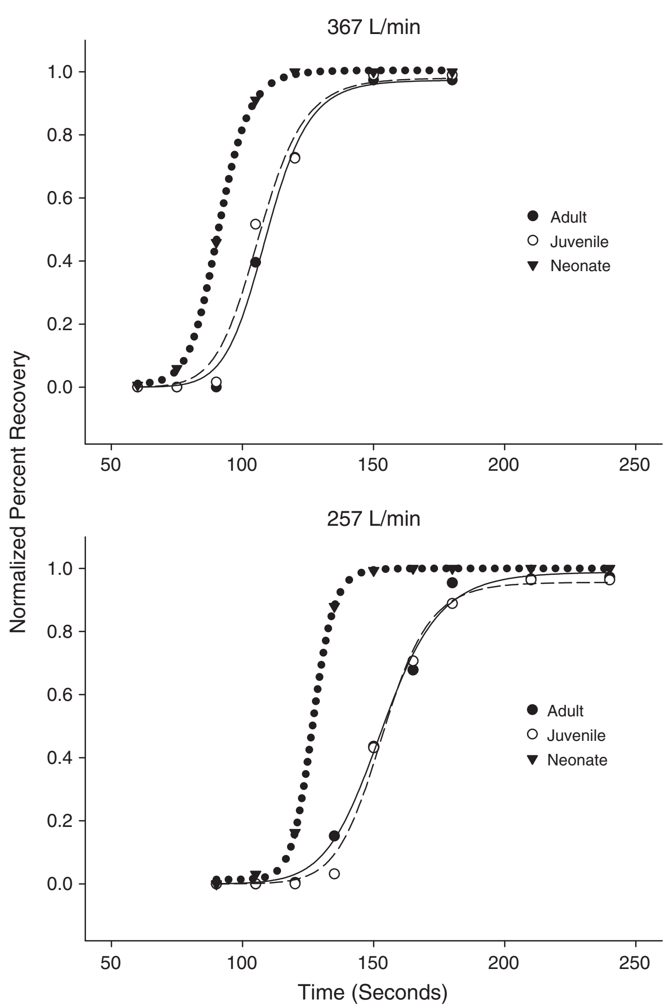

Fig. 3. Average cumulative normalized percent recovery of NZMS at both flow rates fit with a four parameter logistic curve.

3.2. Water transit

Mean residence time for water was shorter at the higher flow rate, but variance across tests was high (Table 4). The mean D/μL calculated for both flow rates ranged between 0.1 and 0.2, indicating a moderate deviation from a true plug flow (Fig. 5). Conductivity measures were similar for both the overflow and underflow (Fig. 6). At flows of 367 L/min the tracer was first detected at the underflow between 60 and 70 s and was no longer detected after 130–140 s, indicating a residence of 70–80 s. At the lower flow the tracer was detected between 90 and 100 s and was not detected after 160–170 s. We calculated 64.4 s and 91.9 s as theoretical times for water travel through the hydrocyclone system for flow rates of 367 and 257 L/min, respectively, based on the volume of the intake hose, and the hydrocyclone volume (394.12 L). The logistic models (Table 5) fit to the normalized tracer RTD compared favorably to similar models established for snail transit, thus supporting our snail sampling timing protocol (Figs. 3 and 6).

4. Discussion

Our study was the first to use cyclonic separation to remove invasive species from an aquaculture facility and provides a promising potential technique for pre-treating water for use in operations. Previous studies reported successful filtering of biological material such as yeast, blood components, or parasite cultures from solution using a hydrocyclone (Ortega-Rivas, 2004; Williams and Evans, 2007). Based on the average specific gravity of 1.33 for live neonate NZMS (Bruce, 2006) along with model simulation data provided by the manufacturer of the hydrocyclone used for this study, the D50, or the diameter that 50% of the particles are removed through the underflow (Arterburn, 2006; Frachon and Cilliers, 1999), would be approximately 36 μm and the D98 or diameter resulting in a 98% particle removal to the underflow would be 80 μm (Michael Trew, Krebs Engineers, personal communication, March 2008). Dried neonate NZMS are at lease 150 μm in size, but they are not spherical. Our calculations and data from our trials suggest that hydrocyclonic separation would remove all sizes of NZMS.

We did not recover all of the snails introduced into the hydrocyclone. The loss of small numbers of adult NZMS in the system was due to potential sampling and/or counting error, but the juvenile and neonate snails were more likely crushed while moving through the pipe and filtration system, as we found shell fragments, and

Table 2
Summary of MANOVA model results for the significance of four parameter estimates from the logistic curves fit to the cumulative percent recovery of three sizes of NZMS at two flow rates.

Variable	DF	Wilks' lambda	F	P
Flow	4	0.035	95.24	<0.0001
Size	8	0.1002	7.55	<0.0001
Flow * size	8	0.382	2.16	0.0627

Table 3
Summary of analysis of variance for significant models for two parameters from the logistic equations fit to the cumulative percent recovery of three sizes of NZMS from the hydrocyclone underflow at two flow rates.

Logistic model parameter	Variable	Mean square	F	P
EC50	Model	2528.51	70.66	<0.001
	Flow	9662.71	270.03	<0.001
	Size	1249.91	34.63	<0.001
	Flow∗size	42.27	1.18	0.331
Hillslope	Model	391.05	5.86	0.002
	Flow	444.41	6.66	0.020
	Size	644.23	9.65	0.002
	Flow∗size	97.88	1.47	0.258

pink fragments characteristic of particles of rose Bengal stained neonates in nets. Hydrocyclones can destroy biological material from the shear forces resulting from tangential feeds into the vortex chamber (Svarovsky, 1984; Williams and Evans, 2007). Williams and Evans (2007) found that a small hydrocyclone with a short vortex cone removed nematodes from rearing solutions with minimal damage. They hypothesized that shorter residence times in the hydrocyclone reduced exposure to shear forces. With a large hydrocyclone and high flows such as in this study, higher shear forces and residence times likely destroyed some biological materials. In addition the 72 m long intake hoses and pipe upstream of the hydrocyclone likely contributed to additional exposure to turbulence and/or friction.

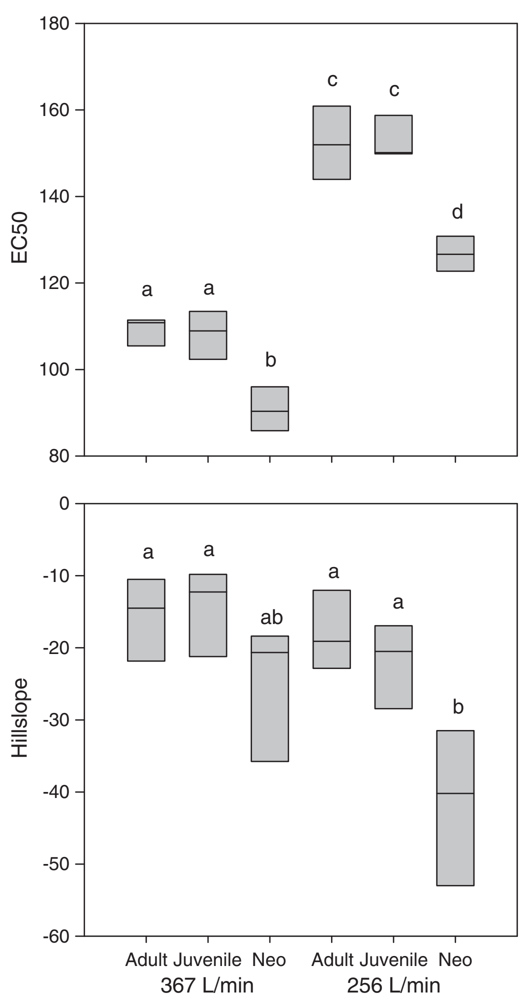

Fig. 4. Comparison of the mean EC50 and hillslope parameter estimates within each flow by size interaction. Different letters note significant differences ($P<0.05$) within each flow by size interaction.

Table 4
Mean residence time, variance, and dispersion ± SD for marker studies evaluating two flows through the hydrocyclone filter at Hagerman National Fish Hatchery.

Flow L/min	Mean residence time ($\bar{t}$, s)	Mean variance (σ^2, s^2)	Mean dispersion number (D/μL, dimensionless)
367	105.31 ± 5.38	1215.54 ± 127.63	0.055 ± 0.008
257 n	120.19 ± 2.42	610.43 ± 186.70	0.021 ± 0.007

At both test flows, we observed that adult and juvenile NZMS traveled at similar rates, but neonate snails moved faster through the system. A hydrocyclone has two vortices: the primary vortex removes particles as they move into the hydrocyclone, and a secondary vortex of water and less dense particles is pulled up through the vortex finder to the overflow (Matvienko and Dueck, 2006; Trawinski, 1976). Laverack (1980) and Matvienko and Dueck (2006) reported that larger particles removed by the primary vortex moved slowly down the side of the vortex chamber and into the vortex cone and form a more viscous layer than the surrounding slurry. The smaller, less dense particles may not be filtered out initially by the primary vortex but experience a higher level of centrifugal force in the smaller and more tightly spinning secondary vortex (Trawinski, 1976). Particles removed by the secondary vortex are removed to the outer part of the primary vortex and moved quickly through the underflow with less friction on the side of the vortex cone (Trawinski, 1976). The neonate NZMS in our study were likely filtered from the secondary vortex, leading to a decreased residence time, but the shape of particles filtered affects filtration rate and efficiency. Particles that are flattened may tend to concentrate more toward the overflow (Trawinski, 1976). Trawinski (1976) discussed how flat particles would be removed through the overflow regardless of how coarse they may be. As NZMS grow they become more elongated and conical, and while their specific gravity dictates they should be filtered out very efficiently, the change in shape may cause an increased residence time for the larger snails.

Our test system was configured for the specific conditions at the test site, to consider the line pressure, drop and flow conditions. Installations at other facilities would need to consider these and other factors that affect performance. If a gravity drop were not available, operation pressure could be generated with a water pump. Our logistic model of snail transit provides a useful tool for discussion and future construction and implementation of this technology as a solution to invasive species infestations in general. The vessel dispersion estimates we calculated are suggestive that a significant amount of mixing occurred in our hydrocyclone system, however, our models of

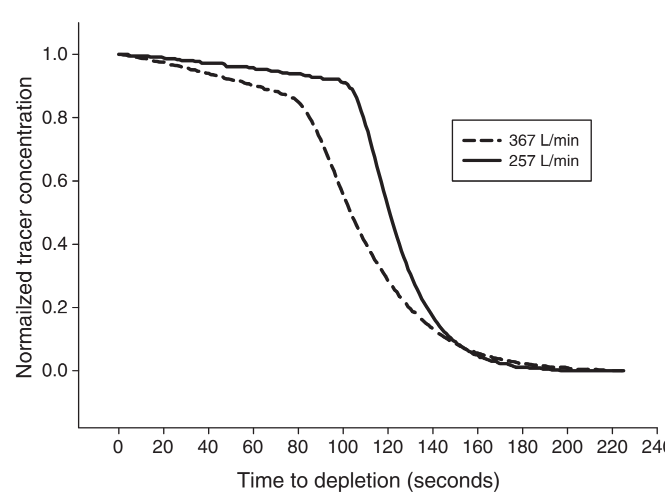

Fig. 5. Average normalized tracer concentration over time of measurement used for step-down trials.

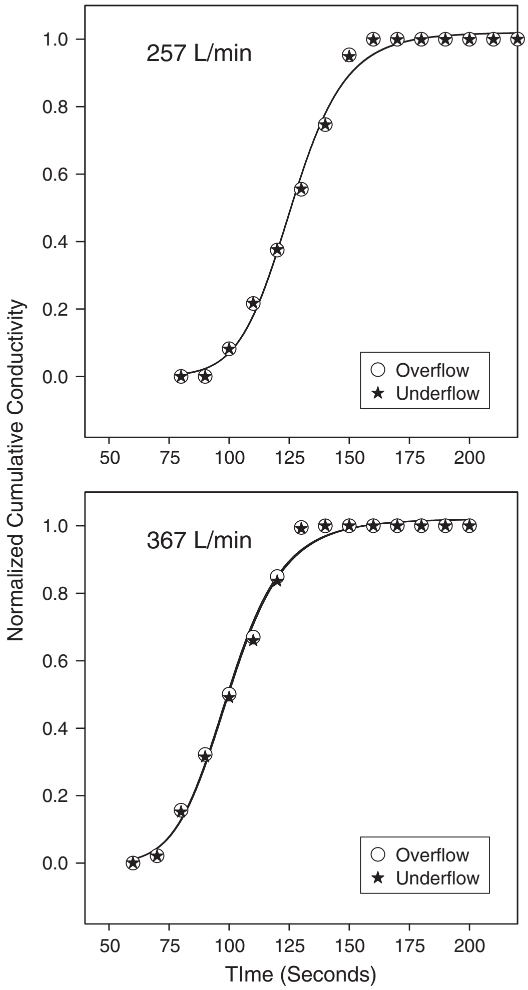

Fig. 6. Logistic curves for underflow and overflow samples of water with NaCl tracer at two test flows. Values were normalized to cumulative conductivity units.

Table 5
Parameter estimates for a four parameter logistic curve for each test completed on the hydrocyclone including the squared residual value and standard error of the estimate.

Flow	Size	Range (min–max)		EC50	Hillslope	R^2	SE
367 L/min	Adult	<0.001	1.00	111.404	−21.850	1.00	0.006
		<0.001	1.01	110.812	−10.519	0.990	0.092
		<0.001	0.98	105.431	−14.512	0.993	0.081
	Juvenile	<0.001	0.99	100.378	−23.787	0.999	0.013
		<0.001	0.99	108.211	−13.498	0.996	0.059
		<0.001	1.03	114.665	−9.395	0.989	0.097
		<0.001	1.00	109.609	−11.048	0.991	0.091
	Neonate	0.0175	1.00	93.827	−17.754	0.999	0.017
		0.0483	1.00	96.708	−40.677	0.999	0.039
		0.0044	1.00	86.832	−20.296	0.999	0.011
		0.0009	0.95	85.525	−21.049	0.992	0.105
257 L/min	Adult	<0.001	0.98	141.798	−10.878	0.988	0.129
		<0.001	1.01	153.544	−15.483	0.998	0.048
		<0.001	0.99	150.317	−22.915	0.999	0.035
		0.0094	1.02	163.310	−22.713	0.997	0.060
	Juvenile	0.0035	0.98	161.596	−31.091	0.999	0.035
		<0.001	0.99	150.126	−20.509	0.995	0.081
		<0.001	0.94	149.759	−15.747	0.985	0.131
		<0.001	0.99	150.126	−20.509	0.995	0.081
	Neonate	<0.001	1.00	126.296	−36.325	1.00	0.0011
		0.0439	1.00	126.934	−44.101	0.999	0.0359
		0.0171	1.00	121.496	−55.966	0.999	0.014
		<0.001	0.99	132.078	−29.881	1.00	0.0027

transit from tracer pulse trials indicated little mixing. Longitudinal mixing would be marked by a quick rise in tracer concentration at arrival and a more gradual depletion as the tracer leaves. Longitudinal mixing is characteristic of fluid moving through a pipe as viscosity of the fluid creates laminar flow (Danckwerts, 1953). Due to the low viscosity of water (1.3 cP at 10 °C, 1.0 cP at 20 °C) there would be some mixing simply due to laminar flow in the hoses even if they were completely straight (Danckwerts, 1953). The hose from the water intake to the hydrocyclone had several bends and different gradients along its course that could have contributed to mixing especially at the higher flow tested, however, we used a non-flexible hose and there were no kinks in the hose delivery system. The step-down tests measured and recorded conductivity instantaneously with a YSI probe placed in a bucket at the underflow, while the pulse test measurements were taken from grab samples at the overflow. The 4 L bucket used for continuous monitoring of conductivity had its own residence time distribution, more like those of a mixed flow reactor, and thus our observations with this probe likely contributed to a rise in estimates of vessel distribution and more mixing than with the pulse trials. With this in mind, we concluded that our hydrocyclone test system most likely had minimal mixing and more closely resembled a plug flow system with some laminar flow in the intake line.

5. Conclusions

This study was conducted with more snail numbers than would likely drift into source waters and be filtered by a hydrocyclone, and our tests were conducted for short periods of time. To further evaluate the feasibility of hydrocyclone filtration to remove invasive NZMS, longer-term evaluations of efficiency should be conducted with naturally occurring drift rates and with mixed sizes of snails. To supply adequate water for a raceway system, we would suggest that hydrocyclones be coupled together in a manifold to achieve the flows needed. Hydrocyclones of 25.4 cm diameter that filter up to 1136 L/min were estimated adequate to remove particles the size of the smallest neonates (Michael Trew, Krebs Engineers, personal communication, March 2008). Since water is often limited at aquaculture operations, this filtration technology could provide uninfested water sources for critical times in the rearing cycle. The underflow of our test hydrocyclone (13.44 L/min) was contaminated but could be filtered additionally with a grit pot designed to catch the filtered particles from the hydrocyclone. Puprasert et al. (2004) reported that this design reduced filtration efficiency of their hydrocyclone by only 5% while returning most of the filtered water to the overflow. We believe additional field trials should include evaluating the efficiency with and without this option.

Acknowledgments

Staff of Hagerman National Fish Hatchery, Hagerman State Fish Hatchery, and the University of Idaho Hagerman Fish Culture Experiment Station provided important assistance and support during field trials. We thank the following students and faculty at the University of Idaho: T. Parker, S. Howard, and K. Hamilton for assistance conducting trials, and Dr. C. Williams for statistical advice. We thank J. Christiansen US Fish and Wildlife Service, Dworshak National Fish Hatchery, and S. Smith, Western Fisheries Research Lab, US Geological Survey, and three anonymous reviewers for their assistance in improving earlier manuscript drafts. Funding for this project was provided by the U.S. Fish and Wildlife Service (P. Heimowitz, project officer), and the U.S. Geological Survey. This is contribution 1098 of the University of Idaho Forestry, Wildlife and Range Resources Experiment Station, Moscow, Idaho. Mention of trade names or commercial products does not constitute endorsement or recommendation by the U.S. government.

References

Abu-Khader, M.M., Badran, O., Attarakih, M., 2011. Ballast water treatment technologies: hydrocyclonic a viable option. Clean Technologies and Environmental 13, 403–413.

Alonso, A., Castro-Díez, P., 2008. What explains the invading success of the aquatic mud snail *Potamopyrgus antipodarum* (Hydrobiidae: Mollusca)? Hydrobiologia 614, 107–117.

Arango, C.P., Riley, L.A., Tank, J.L., Hall Jr., R.O., 2009. Herbivory by an invasive snail increases nitrogen fixation in a nitrogen-limited stream. Canadian Journal of Fisheries and Aquatic Sciences 66, 1309–1317.

Arterburn, R.A., 2006. The Sizing and Selection of Hydrocyclones. FLSmidth Krebs. Available: http://www.flsmidth.com/~/media/PDF%20Files/Liquid–solid%20Separation/Hydrocyclones/Sizing_select_cyclones.ashx. (April 2011).

Bersine, K., Brenneis, V.E.F., Draheim, R.C., Wargo Rub, A.M., Zamon, J.E., Litton, R.K., Hinton, S.A., Sytsma, M.D., Cordell, J.R., Chapman, J.W., 2008. Distribution of the invasive New Zealand musdsnail (*Potamopyrgus antipodarum*) in the Columbia River Estuary and its first recorded occurrence in the diet of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Biological Invasions 10, 1381–1388.

Bondesen, P., Kaiser, W.E., 1949. *Hydroboa* (*Potamopyrgus*) *jenkinsi* Smith in Denmark illustrated by its ecology. Oikos 1, 252–281.

Bowler, P.A., 1991. The rapid spread of the freshwater Hydrobiid snail *Potamopyrgus antipodarum* in the middle Snake River, southern Idaho. Proc Desert Fish Coun, 21, pp. 173–179.

Brenneis, V.E.F., Sih, A., de Rivera, C.E., 2010. Coexistence in the intertidal: interactions between the nonindigenous New Zealand mud snail *Potamopyrgus antipodarum* and the native estuarine isopod *Gnorimosphaeroma insulare*. Oikos 119, 1755–1764.

Bruce, R.L., 2006. Methods of fish depuration to control New Zealand mudsnails at fish hatcheries. University of Idaho Master's Thesis.

Bruce, R.L., Moffitt, C.M., 2010. Quantifying risks of volitional consumption of New Zealand mudsnails by steelhead and rainbow trout. Aquaculture Research 41, 552–558.

Bruce, R.L., Moffitt, C.M., Dennis, B., 2009. Survival and passage of ingested New Zealand mudsnails through the intestinal tract of rainbow trout. North American Journal of Aquaculture 71, 287–301.

Cross, W.F., Rosi-Marshall, E.J., Behn, K.E., Kennedy, T.A., Hall Jr., R.O., El Fuller, E., Baxter, C. V., 2010. Invasion and production of New Zealand mud snails in the Colorado River, Glen Canyon. Biological Invasions 12, 3033–3043.

Danckwerts, P.V., 1953. Continuous flow systems, distribution of residence times. Chemical Engineering Science 2, 1–13.

Davidson, T.M., Brenneis, V.E.F., de Rivera, C., Draheim, R., Gillespie, G.E., 2008. Northern range expansion and coastal occurrences of the New Zealand mud snail *Potamopyrgus antipodarum* (Gray, 1843) in the northeast Pacific. Aquatic Invasions 3, 349–353.

Dybdahl, M.F., Drown, D.M., 2011. The absence of genotypic diversity in a successful parthenogenetic invader. Biological Invasions 13, 1663–1672.

Frachon, M., Cilliers, J.J., 1999. A general model for hydrocyclone partition curves. Chemical Engineering Journal 73, 53–59.

Gerard, C., Lannic, J.L., 2003. Establishment of a new host–parasite association between the introduced invasive species *Potamopyrgus antipodarum* (Smith) (Gastropoda) and *Sanguinicola* sp. Plehn (Trematoda) in Europe. Journal of Zoology 261, 213–216.

Grigorovich, I.A., Korniushin, A.V., Gray, D.K., Duggan, I.C., Colautti, R.I., MacIsaac, H.J., 2003. Lake Superior: an invasion coldspot? Hydrobiologia 499, 191–210.

Hall Jr., R.O., Dybdahl, M.F., VanderLoop, M.C., 2006. Extremely high secondary production of introduced snails in rivers. Ecological Applications 16, 1121–1131.

Haynes, A., Taylor, B.J.R., Varley, M.E., 1985. The influence of the mobility of *Potamopyrgus jenkinsi* (Prosobranchia: Hydrobiidae) on its spread. Archiv für Hydrobiologie 103, 497–508.

Kraipech, W., Chen, W., Dyakowski, T., Nowakowski, A., 2006. The performance of empirical models on industrial hydrocyclone design. International Journal of Mineral Processing 80, 100–115.

Kurtela, Z., Komadina, P., 2010. Application of hydrocyclone and UV radiation as a ballast water treatment method. Promet-Traffic and Transportation 22, 183–191.

Laverack, S.D., 1980. The effect of particle concentration on the boundary layer flow in a hydrocyclone. Chemical Engineering Research and Design 58a, 33–42.

Levenspiel, O., 1984. The Chemical Reactor Omnibook. Oregon State University Book Stores, Corvallis, OR.

Levri, E.P., Dermott, R.M., Lunnen, S.J., Kelly, A.A., Ladson, T., 2008. The distribution of the invasive New Zealand mud snail (*Potamopyrgus antipodarum*) in Lake Ontario Aquat Ecosyst. Health 11, 412–421.

Loo, S.E., Keller, R.P., Leung, B., 2007. Freshwater invasions: using historical data to analyse spread. Diversity and Distributions 13, 23–32.

Matvienko, O.V., Dueck, J., 2006. Numerical study of the separation characteristics of a hydrocyclone under various conditions of loading of the solid phase. Theoretical Foundations of Chemical Engineering 40, 203–208.

Ortega-Rivas, E., 2004. Applications of the liquid cyclone in biological separations. Engineering in Life Sciences 4, 119–123.

Parsons, M.G., Harkins, R.W., 2002. Full-scale particle removal performance of three types of mechanical separation devices for the primary treatment of ballast water. Marine Technology Sname N 39 (4), 211–222.

Ponder, W.F., 1988. *Potamopyrgus antipodarum*—a molluscan colonizer of Europe and Australia. Journal of Molluscan Studies 54, 271–285.

Puprasert, C., Hebrard, G., Lopez, L., Aurelle, Y., 2004. Potential of hydrocyclone and hydrocyclone equipped with grit pot as pre-treatment in run-off water. Chemical Engineering and Processing 43, 67–83.

Richards, D.C., O' Connell, P., Shinn, D.C., 2004. Simple control method to limit the spread of the New Zealand mudsnail *Potamopyrgus antipodarum*. North American Journal of Fisheries Management 24, 114–117.

Schreiber, E.S., Glaister, G.A., Quinn, G.P., Lake, P.S., 1998. Life history and population dynamics of the exotic snail *Potamopyrgus antipodarum* (Prosobranchii, Hydrobiidea) in Lake Purrumbete, Victoria, Australia. Marine and Freshwater Research 49, 73–78.

Svarovsky, L., 1984. Hydrocyclones. Holt, Reinhart, and Wilson, London.

Trawinski, H., 1976. Theory, applications, and practical operation of hydrocyclones. Engineering and Mining Journal 115–127.

Wallace, C., 1992. Parthenogenesis, sex and chromosomes in *Potamopyrgus*. Journal of Mollusc Studies 58, 93–107.

Wang, J.-M., Wang, L.-Z., 2009. Experimental study of a new hydrocyclone for multi-density particles separation. Separation Science and Technology 44, 2915–2927.

Watten, B.J., Honeyfield, D.C., Schwartz, M.F., 2000. Hydraulic characteristics of a rectangular mixed-cell unit. Aquacultural Engineering 24, 59–73.

Williams, D.T., Evans, H.F., 2007. A preliminary investigation into the potential use of a hydrocyclone to concentrate entomopathogenic nematodes from suspension. Biocontrol Science and Technology 17, 155–169.

Winterbourn, M.J., 1970. Population studies on the New Zealand freshwater Gastropod, *Potamopyrgus antipodarum* (Gray). Proceeding of Malacologia Society of London 39, 139–149.

Zaranko, D.T., Farara, D.G., Thompson, F.G., 1997. Another exotic mollusc in the Laurentian Great Lakes: the New Zealand native *Potamopyrgus antipodarum* (Gray 1843) (Gastropoda, Hydrobiidea). Canadian Journal of Fisheries and Aquatic Sciences 54, 809–814.