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Effectiveness of High-Velocity Inclined Profile-Bar Fish Screens Measured by Exclusion and Survival of Early Life Stages of Fathead Minnow

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Abstract.—We estimated exclusion and survival rates of fathead minnow *Pimephales promelas* exposed to four configurations of a high-velocity inclined profile-bar screen. These screens are functionally different from conventional positive-barrier designs because fish behavior and swimming ability are not design considerations. We tested screens inclined at 45° or 60° that had 1.0-mm or 0.5-mm slot widths and used 5–45-mm total length fathead minnow released high or low in the water column. The exclusion rate for 45.0-mm and 22.5-mm fathead minnow was 100%. Survival of 45.0-mm fish was 88%; latent mortalities were attributable to nonscreen causes. Survival of 22.5-mm fish was 100%. Exclusion rates for high- and low-release 12.5-mm fathead minnow were nearly 100%. Survival rates for high-release 12.5-mm fathead minnow were 62–86% and were similar to or higher than those for low-release fish (15–71%). Exclusion rates of 7.5-mm and 5.0-mm fathead minnow in tests with the 0.5-mm screen were 88–95% regardless of release position. Exclusion rates for 7.5-mm and 5.0-mm fish tested with 1.0-mm screens were mostly lower (2–90%), especially for low-release fish. Survival rates for 7.5-mm fathead minnow in high releases were 26–62%, but survival rates for low-release 7.5-mm fish (0–9%) and 5.0-mm fish (28%) were low. The screen angles we tested had little consistent effect on exclusion or survival rates. The successful exclusion and survival we documented for various life history stages of fathead minnow, coupled with the high hydraulic efficiency and self-cleaning properties of high-velocity inclined profile-bar fish screens, indicates that this is a potentially effective tool for managers seeking to reduce entrainment loss of fish in aquatic ecosystems.

Entrainment represents a chronic source of mortality for fish of various life history stages in aquatic ecosystems where unscreened water is removed for domestic consumption, irrigation, electrical generation, or other uses. Estimates of annual entrainment of millions to billions of fish have been documented, and high losses from lentic or lotic systems may affect recruitment (Hergenrader et al. 1982; Jude et al. 1983; Stevens et al. 1985; Jensen 1990; Travnichek et al. 1993). The ubiquitous presence of structures that divert large quantities of irrigation water from streams, particularly in the arid western United States (Clothier 1953; National Research Council 1992; Pringle et al. 2000), suggests that entrainment may have widespread and substantial negative effects on fish community structure and abundance.

Screens are one of the few proven alternatives available to reduce the entrainment of fishes into water diversion structures (Zeitoun et al. 1981; McKay 1987; Weisberg et al. 1987). We tested a relatively new design, a high-velocity inclined profile-bar (wedge-wire) screen (Figure 1), to assess its potential for excluding fish. These screens are also known as static inclined screens, Coanda-effect screens, or sieve bends (Wahl 2001). High-velocity profile-bar fish screens differ from traditional positive barrier configurations. Most barrier screen designs couple low approach velocities (velocity through the screen) with high sweeping velocities (across screen) to effect screening. Low approach velocities reduce fatigue of target life stages and presumably, the frequency of screen contacts. Functionally, low approach velocities allow fish to maintain position upstream of the barrier, while relatively high sweeping velocities move fish downstream past the screen face away from the diversion, a process which may take 1–2 min or more. Traditional screens may also need intermediate bypasses when structures are large and exposure times are high. In contrast, inclined profile-bar screens have water delivered to the top

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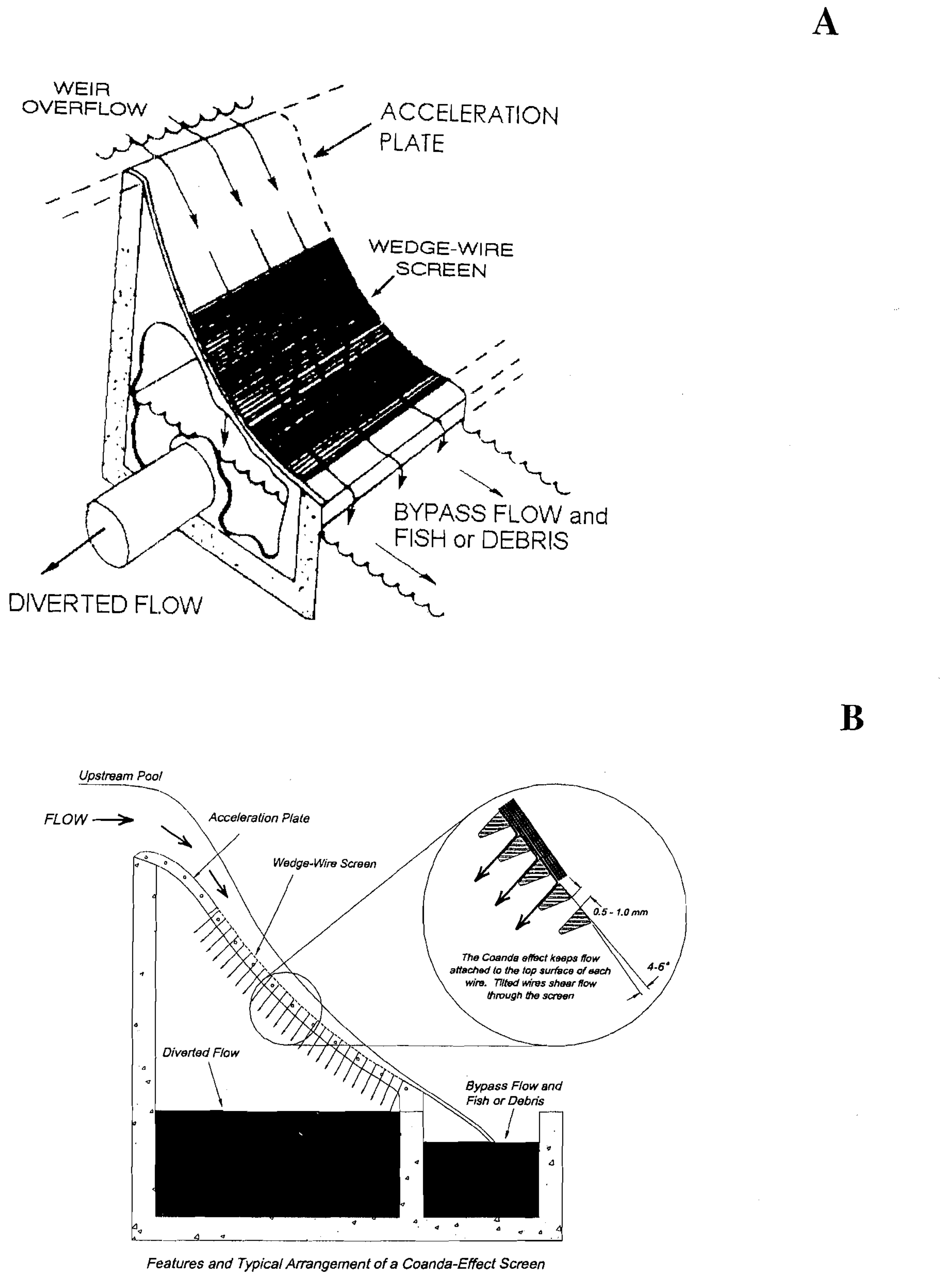

FIGURE 1.—Main features and operation of a typical high-velocity inclined profile-bar screen (panel A). The side view (panel B) depicts the details of profile-bar position, arrangement, and function.

of the screen via an overflow weir, which then flows over the screen face at a high 2–3-m/s velocity. High velocities limit screen exposure time of fish to 1 s or less. Fish do not need to swim to avoid impingement because fish and debris are carried over the weir, swept by overflow off the toe of the screen, and transported back to the stream. Thus, unlike traditional screens, fish behavior and swimming performance and approach and sweeping velocities are not design considerations for high-velocity inclined profile-bar screens. Additionally, high overflow velocity across the screen surface aids in self-cleaning, and because the screens lack moving parts, maintenance is minimized. However, few tests have been conducted to assess the screening effectiveness of inclined profile-bar screens for fish, particularly early life stages.

Our objective was to assess the performance of high-velocity inclined profile-bar fish screens. To accomplish this, we measured exclusion and survival rates of fathead minnow *Pimephales promelas* that passed over different configurations of inclined profile-bar screens with 1.0-mm and 0.5-mm slot widths. The fathead minnow was a useful test animal because it has a generalized body shape that may allow transfer of inferences from screen tests conducted in this study to other species. The only literature we found that described performance of inclined profile-bar screens was for relatively larger-bodied salmonids (>35-mm fork length; Buell 1996, 2000), so we focused on relatively smaller-bodied early life stages.

Methods

Screen description.—Flume and screen models constructed at the Water Resources Research Laboratory, U.S. Bureau of Reclamation, Denver, Colorado, were used for fish screen tests. Inclined profile-bar screens have a flat or concave surface and are typically angled downward 45–60° from horizontal (Figure 1). Water passes over and down an accelerator plate and across the profile-bar screen, and flow is perpendicular to the bars. The individual bars are tilted about 5° downstream, so that the upstream edge of each bar projects slightly into the flow. Each offset bar shears a thin layer of water from the bottom of the flow layer and directs it through the screen. Water passes through the screen because flow remains attached to the bar and is directed through the screen rather than skipping from the high point of one bar to the next. Attachment of flow to the bar surface is an example of the Coanda effect, the tendency of a fluid jet to remain attached to a solid flow boundary (Wahl 2001). Because the bars are wide (1.5 mm) relative to the spacing between them (1.0 or 0.5 mm), and the offset height created by the tilted bars is small (about 0.2 mm for typical screens), the screen surface is relatively smooth.

High-velocity profile-bar screens have a high filtration capacity that increases with overflow rate. Based on empirical and modeling data, Wahl (2001) showed that a hypothetical screen, 1.33 m deep with 1.0-mm slot widths, 1.5-mm-wide screen bars, a 5° wire tilt angle, a 60° incline, and a 10% overflow rate, could screen 0.394 m^3/s per meter of screen width (4.25 ft^3/s per foot). Reducing the screen slot width to 0.5 mm and keeping all other factors constant reduced filtration capacity only by 18%, a surprising result considering that screen porosity was reduced by 38%. This is because much of the filtration capacity derives from the shearing effect described above, which is more dependent on bar tilt angle than screen porosity.

Experimental design.—Our work was performed in a manner consistent with recommendations of the Bioengineering Section of the American Fisheries Society for laboratory evaluation of fish passage technologies. We hypothesized that overflow rate, screen angle, screen slot width, fish length, and fish release point in the water column might affect the exclusion rate and survival of fathead minnow. Therefore, we tested four basic screen and overflow configurations with five different sizes of fish released at high and low positions in the water column. In the first configuration, the screen was inclined 45° from horizontal and had a 1.0-mm slot width and a high (25%) overflow rate. The second configuration was identical to the first except for a 10% overflow rate. The third screen configuration was angled 60° from horizontal and had a 1.0-mm slot width (10% overflow), and the fourth configuration was identical to the third except that the slot width was 0.5 mm. Fathead minnow were used as test animals because they were native to the South Platte River system, Colorado (Propst and Carlson 1986), where screen installation was proposed, and were readily available from a local commercial supplier. Initially, we used five nominal sizes of fathead minnow: 5.0, 7.5, 12.5, 22.5, and 45.0 mm total length (TL; Table 1 presents aspects of the experimental design and levels of replication). This length range was a reasonable representation of the size of fishes that may be at risk of entrainment in the South Platte River. A typical test for a single screen configuration and each nominal fish size involved up to three control groups and two treatment groups because we wanted to partition potential sources of mortality. Batches of fish (10 each except for a few early tests in which 20 fish were used) were double-counted for accuracy and were held in plastic cups. The background control group consisted of randomly selected cups of fish, which were placed in individual bags with oxygen but experienced no net or screen effects. From the net

TABLE 1.—Experimental design and number of replicates used for each screen type, overflow rate (high = 25%, low = 10%), experimental group (three control and two treatment groups), and nominal fish size-classes used to test survival and exclusion of fathead minnow by high-velocity inclined profile-bar screens. Exclusion rates of 5.0-mm fish were estimated for most screen types; because of the high handling mortality of larvae, survival rates were not estimated except for a single test. Thus, assessment of control survival rates, which were used to correct treatment survival rates for handling mortality, was not conducted for most 5.0-mm experimental group combinations.

Screen	Overflow rate	Experimental group	Experimental replicates per nominal fish size-group (mm TL)				
			5.0	7.5	12.5	22.5	45.0
45°; 1.0-mm slot width	High	Background control		3	3		
		Net recovery control		3	3		
		Screen control		5	5		
		High release	5	5	5		
		Low release	5	5	5		
45°; 1.0-mm slot width	Low	Background control		3	3		
		Net recovery control		3	3	3	3
		Screen control		5	5	5	5
		High release	5	5	5	5	5
		Low release	5	5	5		
60°; 1.0-mm slot width	Low	Background control		3	3		
		Net recovery control		3	3		
		Screen control		5	5		
		High release	5	5	4		
		Low release	5	5	5		
60°; 0.5-mm slot width	Low	Background control		3			
		Net recovery control	3	3	3		
		Screen control	5	5	5		
		High release	10	5	5		
		Low release	10	5	5		

recovery control group, we estimated the rate of net recovery and handling mortality by recovering batches of 10 fish that were poured into the capture net. Fish were carefully washed out of the cod end of the net into a plastic pan, counted, and bagged as previously described. Those results ensured that fish health and recovery techniques were consistent over all tests. The screen control was used to estimate mortality from handling, capture, and possible impingement of fathead minnow as high-velocity flow carried fish into the net at the toe of the screen. In each configuration, the lower portion of the screen was covered with a smooth layer of duct tape to reduce the functional screen surface area for hydraulic tests. Batches of 10 fish each were introduced over the tape, washed by overflow into the capture net placed below the toe of the screen, and held in the current for an amount of time (3 s) equivalent to that in the high- and low-release treatments (described below). Net mouth dimensions were 10 × 61 cm, the bag depth was 90 cm, and the mesh size was 363 μm. Net width was equal to that of the screen sideboards to prevent fish loss. Recovered fish were enumerated and treated as described above. Thus, we assumed that screen control fathead minnow experienced similar conditions to screen treatment groups except that the screen control fish were not exposed to the screen. Because fathead minnow in the 5.0-mm size-class were very fragile and susceptible to high handling mortality, our intent was to assess only screen exclusion rates but not posttreatment survival. Therefore, control groups, which were used mostly to correct treatment group survival rates for handling mortality, were not needed for the 5.0-mm size-class. We did make a single fortuitous net recovery, screen control, and posttreatment survival assessment ($N = 5$ replicates) of 5.0-mm fish for the 60° 0.5-mm-slot-width screen. This resulted when we measured fish posttreatment for a presumptive 7.5-mm fish experiment and found that sizes corresponded more closely to the 5.0-mm test group (mean = 6.1 mm TL).

High- and low-release tests were used to determine differences in exclusion and survival rates of fish that approach the overflow weir at different depths in the water column and hence affect the frequency of screen encounters. High- and low-release treatment fish were introduced at the top of the overflow weir above the accelerator plate. High-release fish were introduced to the model by pouring them from a cup held just above the water surface. Low-release fish were introduced directly over the accelerator plate by first placing the batch of fish in a stoppered length of clear, flexible plastic tubing (12.7-mm diameter) attached to a steel rod. The stoppered end of the tubing was positioned at the bottom of the water column over the accelerator plate; when the net was in position, the stopper was pulled from the tube by a cord. Fathead minnows were swept over the length of the screen and captured at the toe as described for screen control fish. One high-release replicate from the 60° 1.0-mm-slot-width screen tests with 12.5-mm fathead minnows was destroyed after recapture, so only four replicates were available for survival estimates.

Test fish were transported in coolers to the Aquatic Research Laboratory in Fort Collins, Colorado, and held in 2-L overflow tanks supplied with well water at 18°C. Fish mortality was monitored daily for 4 d posttreatment, and brine shrimp *Artemia* spp. nauplii were offered ad libitum twice per day. We measured TL and maximum cross-section diameter of fathead minnow used in each test batch.

Data analysis.—The percentage of fish that were excluded by the screen and the percentage of fish that survived releases for 4 d posttreatment were the experimental response variables. Survival rates were computed from the number of screened fish that survived divided by the total number of excluded fish; fish that passed through the screen were not included. The mortality of fish in the screen controls, which was due to combined effects of background factors, handling, and turbulence in the capture net, was used to adjust mortality rates of fish in high and low releases. We accomplished this by use of Abbott's formula:

$$p_c = (p_o - p)/(1 - p),$$

where p_c, p_o, and p are the corrected, original, and screen control mortality proportions, respectively (Newman 1995). Abbott's formula is commonly used to correct treatment survival rates when control animals die. The percentage of fish excluded and the percentage surviving ($1 - p_c$) were compared to determine effects of two overflow rates and three screen types, each having different combinations of screen slot widths (1.0 mm, 0.5 mm) and screen angles (45°, 60°), high and low release points, and five nominal fish lengths. We used multifactor analysis of variance (ANOVA) to assess differences in exclusion and survival rates among treatments as a function of the explanatory variables, screen type and release point, and their interaction. The proportions of fish that were excluded or that survived were transformed (arcsine and square root) prior to analysis to stabilize variances and normalize the data. Preliminary analysis suggested complex interactions among size-groups and other experimental effects, so ANOVA analyses were conducted by fish size-class to enhance interpretation. Significant interactions between the main effects of screen type and release point warranted several comparisons because each of the three screens had different combinations of two characteristics, screen angle and slot width. Therefore, comparisons for effects of screen angle were restricted to those between the 45° and 60° screens with 1.0-mm slot widths for high and low releases (two comparisons); the 60° 0.5-mm-slot-width screen was excluded. Similarly, to discern effects of slot width, we only compared the 60° screens with 1.0- or 0.5-mm slot widths for high and low releases (two more comparisons); the 45° 1.0-mm-slot-width screen was excluded. Finally, comparisons were made between high and low releases for each of the three screen types, for a total of seven possible comparisons. Only main effects were analyzed when the interaction was not significant, which resulted in fewer comparisons. Least-squares means (LSM) were used to compare means for exclusion and survival data for different release positions, slot widths, or screen angles. We made no adjustments to alpha levels for the purpose of error protection when two or more LSM comparisons were made, which allows the reader to evaluate inferences from significance tests. We also report means, standard errors, and sample sizes for exclusion and survival rate data, which allows readers to draw their own comparisons among treatment combinations of interest and avoids the difficulties posed by numerous hypothesis tests (Yoccoz 1991; Johnson 1999; Anderson et al. 2001).

Results

The survival rate of background control and net recovery control fish increased with size. Survival of 45.0-mm and 22.5-mm fathead minnow in net recovery controls was 100% for the only screen configuration tested (45° 1.0-mm slot width). The 12.5-mm fathead minnow had a mean background survival rate of 97% (87–100%) and a mean net recovery survival rate of 92% (87–97%) for all four screen configurations tested. Likewise, 7.5-mm fathead minnow had mean background and net recovery survival rates of 93% (83–97%) and 62% (40–87%), respectively. The single 5.0-mm fish net recovery control had a survival rate of

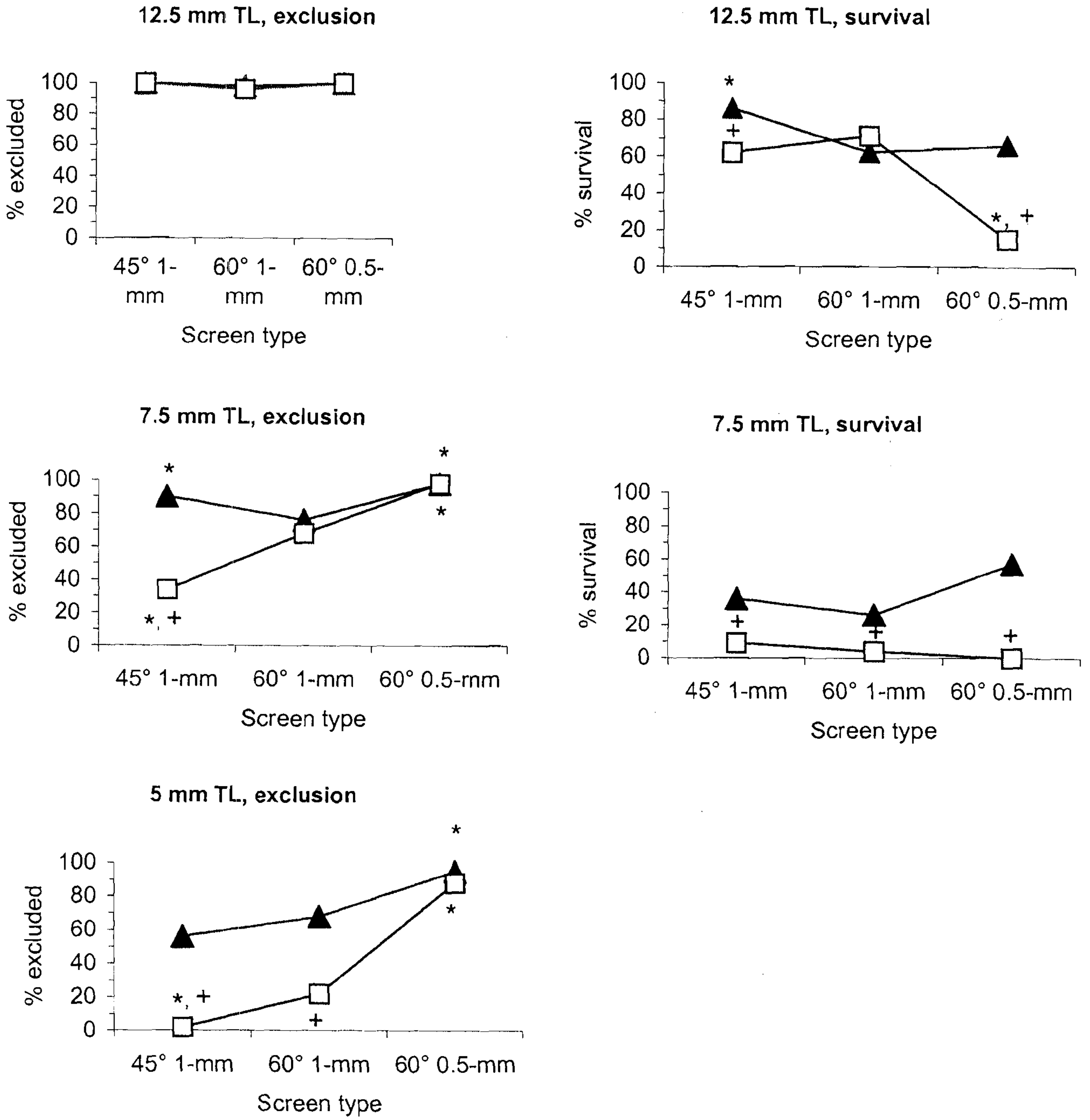

FIGURE 2.—Mean exclusion and survival rates of 12.5-, 7.5-, and 5.0-mm total length (TL) fathead minnow released over three different screen configurations at low (squares) or high (triangles) positions in the water column. Screen control survival rates (Table 2) were used to adjust treatment survival rates for handling and turbulence effects based on Abbott's formula; there were no controls for exclusion data. Screens were inclined at either 45° or 60°, had 1.0-mm or 0.5-mm slot widths, and low (10%) overflow rates. An asterisk adjacent to a high- or low-release trial mean symbol indicates a statistically significant difference ($P \leq 0.05$) with the corresponding high- or low-release trial mean to the right (comparison of screen angle; 45° or 60° screens with 1.0-mm slot widths) or to the left (comparison of slot width; 60° angle with 1.0-mm or 0.5-mm slot widths). No comparisons were made between means for the 45° 1.0-mm screen and the 60° 0.5-mm screen. A plus sign adjacent to a low-release trial mean symbol indicates a statistically significant difference ($P \leq 0.05$) with the corresponding high-release trial for a particular screen type. Standard error bars for means are not presented here (see Table 2) to avoid confusion with significance test symbols.

TABLE 2.—Mean exclusion and survival rates (%; SE and number of replicates in parentheses) of 12.5-, 7.5-, and 5.0-mm TL fathead minnow released over four different high-velocity inclined profile-bar screen configurations. Survival rates of high- and low-release fish were corrected by Abbott's formula based on screen control survival rates. Screen overflow rates were 10% (low) or 25% (high) of the total flow entering the screen model. Screen control (SC) fish were released over the lower surface of the screen where the profile bars were covered by tape. High-release (HR) and low-release (LR) fish entered the screen model at the surface and the bottom of the water column, respectively.

Fish size (mm)	Screen and treatment type					
	45°, 1.0-mm slot width, high overflow			45°, 1.0-mm slot width, low overflow		
	SC	HR	LR	SC	HR	LR
			Exclusion rates			
12.5	100	100	98 (2.5, 5)	100	100	100
7.5	100	76 (2.3, 5)	16 (4.0, 5)	98 (2.0, 5)	90 (5.5, 5)	34 (9.1, 5)
5.0		48 (17.5, 5)	2 (2.0, 5)		56 (6.8, 5)	2 (2.0, 5)
			Survival rates			
12.5	56 (9.3, 5)	36 (14.9, 5)	4 (3.6, 5)	100	86 (9.3, 5)	62 (9.7, 5)
7.5	2 (2.0, 5)	0	0	37 (8.6, 5)	36 (10.1, 5)	9 (9.1, 5)
5.0						

47%. Results for screen controls are presented separately.

Fathead minnow (12.5-, 7.5-, and 5.0-mm TL) released in the 45° 1.0-mm-slot-width screen with a 25% overflow were subjected to high turbulence upon capture, and some fish may have backwashed out of the capture net. In spite of this, exclusion rates for the 45° 1.0-mm-slot-width screen in high overflow tests were only slightly lower than those for low overflow tests, regardless of release position (Table 2). Because fish loss may have biased exclusion rates in high overflow tests, those data were excluded from statistical analysis. Turbulent flows also caused nearly total impingement mortality of fish in the capture net, so all other screen configurations were tested with a lower, 10% overflow rate. Potential implications of high screen overflow rates in a natural setting are discussed later.

45.0-mm and 22.5-mm Fathead Minnow

Tests with the 45° 1.0-mm-slot-width screen and a high release position showed that 100% of fathead minnow were excluded. Survival of 45.0-mm fish was 88%, but mortality was likely due to poor fish condition and a secondary bacterial infection contracted prior to tests. The survival rate of 22.5-mm fish was 100%. Because exclusion and survival rates for these relatively large fish were high, further tests on other screens were conducted only with smaller life stages.

12.5-mm Fathead Minnow

The mean exclusion rates of 12.5-mm fathead minnow (actual mean TL = 11.9 mm; 95% confidence interval [CI] = 11.5–12.3; mean maximum diameter = 2.0 mm) were 96–100% for all screen types and release points (Figure 2). The two-factor ANOVA that evaluated the proportion of fathead minnow excluded as a function of screen configuration (three types), release point (high and low), and their interaction was not statistically significant (F = 1.68; df = 5, 24; P = 0.178), so no further interpretation was needed.

The mean survival rate of 12.5-mm fathead minnow in all tests ranged from 15% to 86%. The two-factor ANOVA that assessed survival of 12.5-mm fathead minnow as a function of screen type, release point, and their interaction was statistically significant (F = 6.74; df = 5, 23; P = 0.005). The interaction (P = 0.012; Table 3) was complicated because high-release fish did not always survive at higher rates than low-release fish. The survival rate of 12.5-mm fathead minnow in high-release tests was higher with the 45° screen (86%) than with the 60° screen (62%; P = 0.05); the survival rate was similar (P = 0.52) for low-release fish released over the 45° screen (62%) and the 60° screen (71%; Figure 2). High-release fish survived at similar rates (P = 0.47) when released over 1.0-mm (62%) and 0.5-mm (66%) slot-width screens. Low-release fish survived poorly (15%) over the 0.5-mm-slot-width screen compared to the 1.0-mm-slot-width screen (71%; P = 0.0006). High-release fathead minnow survived at higher rates than low-release fish in tests with the 45° 1.0-mm-slot-width screen (86% and 62%, respectively; P = 0.04) and the 60° 0.5-mm-slot-width screen (66% and 15%, respectively; P = 0.0004), but were similar (62% and 71%, respectively; P =

TABLE 2.—Extended.

Fish size (mm)	Screen and treatment type					
	60°, 1.0-mm slot width, low overflow			60°, 0.5-mm slot width, low overflow		
	SC	HR	LR	SC	HR	LR
			Exclusion rates			
12.5	100	98 (2.0, 5)	96 (2.5, 5)	100	100	100
7.5	100	76 (2.5, 5)	68 (8.6, 5)	100	98 (2.0, 5)	98 (2.0, 5)
5.0		68 (8.6, 5)	22 (8.6, 5)	100	95 (2.7, 10)	88 (2.5, 10)
			Survival rates			
12.5	100	62 (10.9, 4)	71 (8.6, 5)	80 (7.1, 5)	66 (5.0, 5)	15 (4.7, 5)
7.5	52 (15.0, 5)	26 (11.6, 5)	4 (4.2, 5)	62 (8.1, 5)	57 (3.3, 5)	0
5.0				56 (4.0, 5)	28 (16.5, 5)	0

0.54) in tests with the 60° 1.0-mm-slot-width screen.

7.5-mm Fathead Minnow

The mean exclusion rates of 7.5-mm fathead minnow (actual mean TL = 6.9 mm; 95% CI = 6.6–7.1 mm; mean maximum diameter = 0.85 mm) were 34–98% for all screen types and release points (Table 2; Figure 2). The overall two-factor ANOVA that evaluated the proportion of fathead minnow excluded as a function of screen configuration, release point, and their interaction was statistically significant ($F = 17.91$; df = 5, 24; $P < 0.0001$), and the interaction was again a significant effect ($P = 0.0003$; Table 3). High-release fish released over the 45° 1.0-mm-slot-width screen were excluded at a higher rate (90%) than high-release fish tested with the 60° 1.0-mm-slot-width screen (76%; $P = 0.03$). Low-release fish released over the 45° 1.0-mm-slot-width screen were excluded at a lower rate (34%) than low-release fish tested with the 60° 1.0-mm-slot-width screen (68%; $P = 0.004$). High-release fish tested with the 60° 0.5-mm-slot-width screen were excluded at a higher rate (98%) than high-release fish in the 60° 1.0-mm-slot-width screen tests (76%; $P = 0.0009$). Similarly, low-release fish released over the 60° 0.5-mm-slot-width screen had a higher exclusion rate (98%) than low-release fish in the 60° 1.0-mm-slot-width screen tests (68%; $P = 0.0002$). High-release fish were excluded at a higher rate (90%) than low-release fish (34%) when released over the 45° 1.0-mm-slot-width screen ($P < 0.0001$); exclusion rates of high-release fish (76%) and low-release fish (68%) released over the 60° 1.0-mm-slot-width screen ($P = 0.52$) were not significantly different. Exclusion rates for high- and low-release fish in the 60° 0.5-

TABLE 3.—Analysis of variance (ANOVA) statistics for models that assessed the effects of screen type, fish release position, and the screen × release position interaction on exclusion and survival rates of various sizes of fathead minnow in tests of high-velocity inclined profile-bar screens. Overall ANOVA model results are given in the text.

Model	Effect	df	Sum of Squares	*F*	*P*
12.5 mm TL; survival	Screen	2	0.82151	5.85	0.0089
	Release position	1	0.71078	10.12	0.0042
	Screen × release position	2	0.75249	5.36	0.0123
7.5 mm TL; exclusion	Screen	2	1.76288	25.72	<0.0001
	Release position	1	0.52799	15.40	0.0006
	Screen × release position	2	0.77879	11.36	0.0003
7.5 mm TL; survival	Screen	2	0.14131	0.91	0.4162
	Release position	1	2.25853	29.07	<0.0001
	Screen × release position	2	0.41200	2.65	0.0911
5.0 mm TL; exclusion	Screen	2	6.01255	68.40	<0.0001
	Release position	1	2.50861	57.07	<0.0001
	Screen × release position	2	0.63383	7.21	0.0025

mm-slot-width screen tests (each 98%) also did not differ.

The mean survival rate of 7.5-mm fathead minnow in all tests ranged from 0% to 57%. Release position was the primary factor affecting fathead minnow survival ($P = 0.0006$); screen type and the screen × release position interaction were not significant effects in the overall ANOVA model ($F = 7.24$; df = 5, 24; $P = 0.0003$). The average survival rate of high-release fish was 40%, compared to just 4% for low-release fish ($P < 0.0001$; Table 3). Survival of high-release fish was significantly higher than that of low-release fish for the 45° 1.0-mm-slot-width screen (36% and 9%, respectively; $P = 0.03$), the 60° 1.0-mm-slot-width screen (26% and 4%, respectively; $P = 0.05$), and the 60° 0.5-mm-slot-width screen (57% and 0%, respectively; $P < 0.0001$). Survival rates of low-release 7.5-mm fathead minnow were not significantly different from zero.

5.0-mm Fathead Minnow

Mean exclusion rates of fathead minnow in the nominal 5.0-mm group (actual mean TL = 5.9 mm; 95% CI = 5.8–6.0 mm; mean maximum diameter = 0.7 mm) ranged from 2% to 95%. The significant two-factor ANOVA ($F = 39.34$; df = 5, 34; $P < 0.0001$) and the significant interaction effect ($P = 0.0025$) indicated that exclusion rates were higher for high-release fish than for low-release fish and slightly higher for 60° screens than for 45° screens. High-release fish released over the 45° 1.0-mm-slot-width screen were excluded at a lower rate (56%) than high-release fish tested with the 60° 1.0-mm-slot-width screen (68%; $P = 0.20$). Low-release fish released over the 45° 1.0-mm-slot-width screen had a lower exclusion rate (2%) than low-release fish tested with the 60° 1.0-mm-slot-width screen (22%; $P = 0.009$). High-release fish in tests with the 60° 0.5-mm-slot-width screen were excluded at a higher rate (95%) than high-release fish released over the 60° 1.0-mm-slot-width screen (68%; $P = 0.0008$). Likewise, low-release fish were excluded at a higher rate when released over the 60° 0.5-mm-slot-width screen (88%) than when released over the 60° 1.0-mm-slot-width screen (22%; $P < 0.0001$). High-release fish were excluded at higher rates than low-release fish when released over the 45° 1.0-mm-slot-width screen (56% and 2%, respectively; $P < 0.0001$), the 60° 1.0-mm-slot-width screen (68% and 22%, respectively; $P < 0.0001$), and the 60° 0.5-mm-slot-width screen (95% and 88%, respectively; $P = 0.036$). The fortuitously collected survival rate data for 5.0-mm fathead minnow in 60° 0.5-mm-slot-width screen trials with high releases averaged 28%, compared to 0% for low-release fish; no other survival data were collected for 5.0-mm fathead minnow.

Posttreatment mortality patterns were consistent across trials and fish sizes. Most fathead minnow that succumbed did so within 1–2 d after tests were conducted. Although the cause of mortality was not evident in all trials, some of the fish mortalities from low-release treatments had missing eyes, disrupted abdominal regions, or craniums that were distended or torn.

Discussion

High-velocity inclined profile-bar screens effectively excluded most life history stages of fathead minnow in laboratory tests and may have application in field situations. High exclusion and survival of 45.0- and 22.5-mm fathead minnow screened by the 45° 1.0-mm-slot-width screen at the low overflow rate with a high release point suggested that additional tests of other profile-bar screen configurations with those size-classes would yield similar results. Thus, we chose to concentrate additional effort on smaller life stages. Further justification for not focusing on larger life stages was given by Buell (1996, 2000), who found 100% survival and low injury rates for larger juvenile rainbow trout *Oncorhynchus mykiss* (mean fork length [FL] = 36–189 mm) and Chinook salmon *O. tshawytscha* (mean FL = 37–75 mm) that passed over a similar screen.

In our experiments, larger fathead minnow were excluded and survived at higher rates than small fish. Nearly 100% of 12.5-mm and larger fathead minnow were excluded, and their survival rates were usually 60% or higher. We anticipate that fish larger than the ones we tested would also be efficiently screened and should survive at high rates if the receiving water is of adequate volume and if the screen toe is well-watered. Conversely, exclusion rates for 5.0-mm fathead minnow were lower (except for the 0.5-mm-slot-width screen), and survival was low. Exclusion rates for 7.5-mm fish were intermediate between the 5.0- and 12.5-mm size-classes, but survival rates for 7.5-mm fish were generally low, especially in the low release position. Survival rates of small-bodied fish are confounded somewhat by high handling mortality, so the true effects of the screen on survival are difficult to discern.

A comparison of slot width with the maximum diameter of fathead minnow showed that screening was relatively efficient. For example, fathead minnow in the 7.5-mm group had a mean maximum cross-sectional diameter of about 0.85 mm, and likely a smaller compressible distance when alive. However, in low and high releases, the 1.0-mm-slot-width screens excluded an average of 67% of all fish tested. The exclusion rate for 5.0-mm fathead minnow was higher than expected (62%) in high releases for the 1.0-mm screen, given that their maximum diameter was 0.7 mm. However, the exclusion rate for low-release 5.0-mm fathead minnow tested with a 1.0-mm screen averaged only 12%, suggesting that individuals that had multiple encounters with screen slots larger than the fish's maximum diameter would usually be lost. High exclusion rates (96–100%) of 12.5-mm fish were likely because the mean maximum diameter of fathead minnow used was 2.0 mm, or twice as wide as the widest screen slot width tested.

The exclusion efficiency of high-velocity inclined profile-bar screens used in this study was difficult to compare with that of existing studies because none have been completed with similar-sized fish (Buell 1996, 2000) and no studies have examined survival rates of screened fish. Other profile-bar screen tests of exclusion rates have been conducted, but they used the traditional positive barrier design for which approach velocities are comparatively low (e.g., 13–20 cm/s; Zeitoun et al. 1981; Weisberg et al. 1987). In spite of the functional differences between these approaches, some comparisons are warranted. Similar to our study, others found that larger fish were excluded at higher rates than smaller fish, and that a 1.0-mm-slot-width screen excluded most fish 10-mm TL or longer (Zeitoun et al. 1981; Weisberg et al. 1987, references therein). Weisberg et al. (1987) also found that more fish were excluded by a given slot width than would be expected based on the maximum width of the larvae. They suggested that, in addition to direct physical exclusion, cylindrical profile-bar screens have a hydrodynamic exclusion function that allows even weak-swimming larvae to escape the flow field. Hydrodynamic exclusion was enhanced by flows perpendicular to the screen that exceeded through-screen velocities and swept larvae away from the screen (Weisberg et al. 1987), in a manner similar to sweeping velocities in front of the traditional stationary barrier-type screens. Such an exclusion mechanism may have operated in our experiments as well, even though water velocities over inclined profile-bar screens were very high. As high-velocity water swept larvae across the inclined screen face, entrainment likely occurred only when a larva happened to align precisely with the slot axis.

Release position and screen configuration had important but often interacting effects on exclusion and survival rates of 12.5-mm or smaller fathead minnow. For those size-classes, fathead minnow released high in the water column generally had similar or higher exclusion and survival rates than fish released low in the water column. This may have occurred because high-release fish had fewer screen contacts and a lower likelihood of entrainment. Fewer screen contacts should also reduce the physical damage to fish and increase survival. Examination of dead fish recovered in tests suggested that physical abrasion from the screen may have been the cause of mortality. From an application perspective, these data suggest that knowledge of the vertical distribution of fish species and life history stages in diverted water may guide expectations about the efficacy of screening to reduce entrainment loss.

The effects of screen angle on exclusion rates of fathead minnow were mixed, but rates were generally higher for the 60° screen than the 45° screen. The effects of screen angle on survival rates were also mixed, but survival was slightly higher for the 45° screen than for the 60° screen. Thus, the screen angles we tested may not play a prominent role in determining exclusion and survival rates of fathead minnow.

The effects of slot width on the exclusion of fathead minnow in screen tests were more clear-cut. The 12.5-mm fathead minnow were effectively excluded by 1.0- and 0.5-mm screens; the 0.5-mm-slot-width screen excluded substantially more 5.0–7.5-mm fathead minnow than the 1.0-mm-slot-width screen. The effects of slot width on survival were mixed. More high-release fish survived in tests with the 0.5-mm-slot-width screen than in tests with the 1.0-mm-slot-width screen, but low-release fish survived poorly, especially in tests with the 0.5-mm screen. Poor survival of low-release fathead minnow may have been due to higher frequency of screen contacts, because profile bars in the 0.5-mm screen were more closely spaced per unit of screen length compared to the 1.0-mm screen. Although we did not assess post-treatment survival of 5.0-mm fathead minnow in most tests because of high handling mortality, observations suggested that most of the recaptured fish that passed over the screen were moribund or dead.

The role of screen slot size on fish exclusion rates in other studies has been less clear (Zeitoun et al. 1981; Weisberg et al. 1987). For example, Weisberg et al. (1987) were unable to detect statistically significant differences in entrainment rates of bay anchovy *Anchoa mitchilli* or naked goby *Gobiosoma bosc* among screens with slot widths of 1.0, 2.0, and 3.0 mm. However, entrainment rates of 8–10-mm TL or larger bay anchovy and 7–8-mm TL or larger naked goby were progressively and substantially reduced in tests of smaller slot-width screens. Weisberg et al. (1987) suggested that the low numbers of entrained larvae collected in their study resulted in low statistical power to detect an effect of slot width, a result common to other studies (Zeitoun et al. 1981).

We hypothesized that screen overflow rate may have implications for fish position in the water column and, subsequently, entrainment and survival rates. We thought this because higher overflow rates should reduce the average frequency of fish contact with the screen, thereby reducing entrainment and mortality rates. However, exclusion rates of fathead minnow in high overflow tests were similar to, or slightly lower than, those in low overflow tests. This may be due, in part, to the backwash of fish from the capture net by turbulence during high overflow tests. Estimates of survival rates of fathead minnow in high overflow tests were similarly confounded by high net impingement mortality, and could not be adjusted with screen control survival rates because survival was often zero. Thus, the conclusions we can draw from these laboratory tests about effects of overflow rate on exclusion and survival of fish are equivocal. In a field application, where survival of fish passing over a screen is not confounded by handling mortality, overflow rates higher than 10% (the low rate we used) may not be problematic as long as fish are not exposed to excessive turbulence or physical abrasion upon entering the receiving water. The means to design a high-velocity screen with a low-velocity and relatively benign tailwater are discussed in Buell (2000).

We demonstrated successful exclusion and some level of survival for a variety of life stages of fathead minnow in our screen tests; we are therefore compelled to comment on the generality of our results for other fishes. The general morphology of fathead minnow suggested to us that inferences from our tests were transferable to other species with similar or larger body sizes through ontogeny. Our results should also be general for many fish species and life stages because differences in swimming ability, which importantly affect traditional barrier screen designs, are not likely to affect exclusion and survival rates of fish that pass quickly over high-velocity inclined profile-bar screens.

Criteria for selection of a particular inclined screen type should consider the life stage and size of fish targeted for exclusion. Our tests suggested that most fathead minnow 12.5 mm or larger should be excluded and survive at relatively high rates, regardless of screen angle or slot width. Screens with 0.5-mm slot widths are recommended for maximum exclusion of fish in the two smallest size-classes we tested. Managers should also consider the relative merits of screening many small fish that have high natural mortality rates compared to the benefit of screening fewer larger individuals that may have more positive benefit for the fish community should they reproduce. Techniques to estimate those relative merits, and the effects of recruitment forgone as a result of entrainment loss of early life stages of fish, have been discussed elsewhere (Rago 1984; Jensen 1990).

Screen selection criteria should also consider the hydraulic capacity and self-cleaning capability of each screen in relation to the quantity and type of debris anticipated in the stream (Wahl 2000, 2001). Weir modifications to maintain screen overflow may also be needed to reduce the potential for stranding fish on the screen toe when flows are reduced (Strong and Ott 1988). If these design issues can be overcome, managers of water diversion projects that require a low-maintenance screen to exclude relatively small life stages of fish and debris may want to consider high-velocity profile-bar screens as an alternative to more traditional designs.

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