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Mortality and injury rates for small fish passing over three diversion dam spillway models

Kevin R. Bestgen[a,*], Brent Mefford[b], Robert I. Compton[c]

[a] Larval Fish Laboratory, Department of Fish, Wildlife, and Conservation Biology, 1474, Colorado State University, Fort Collins, CO 80523, United States
[b] U. S. Bureau of Reclamation, Water Resources Research Laboratory, Denver Federal Center, Denver, CO 80225-0007, United States
[c] Wyoming Game and Fish Department, 1212 S. Adams Street, Laramie, WY 82070, United States

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ABSTRACT

Effects of low-head diversion dam spillways on survival and injury of fish passing downstream are poorly understood, especially for fragile, early life stages. The ubiquitous nature of diversion dams in waterways worldwide led us to assess survival and injury rates for small and large size-classes (nominal mean total lengths 25 and 50 mm, respectively) of morphologically general fishes: fathead minnow *Pimephales promelas*; hybrid rainbow × cutthroat trout (*Oncorhynchus mykiss* × *O. clarkii*, hereafter trout); and small razorback sucker *Xyrauchen texanus*. Fish were released in three laboratory spillway models: a 5.7-m-high, free-impinging overfall spillway (0.023 $m^3 \cdot s^{-1} \cdot m^{-1}$) with three stilling basin depths; a 5.4-m-high, smooth-faced ogee-shaped spillway; and the ogee-shaped spillway fitted with energy dissipation steps. Ogee-shaped spillway flows were 0.012–0.24 $m^3 \cdot s^{-1} \cdot m^{-1}$. Mean survival proportion, corrected for handling mortality, was high in all models (0.97–1.0) for all species, size-classes, and flow conditions, except in the free-overfall spillway with stilling basin depth of 2.5 cm, where survival was lower (0.78–0.94). Survival rates of fathead minnows and trout were similar in the stepped and smooth spillway experiments, and across all flow levels. Survival of razorback suckers was slightly lower in the stepped than the smooth spillway but differences were likely due to poor fish condition, which may have also reduced their survival at the highest flows in ogee-shaped spillway models. The free-overfall spillway caused negligible injury to small fish if receiving pool depth was 15 cm or deeper. Injury rates in the stepped spillway were slightly higher than in smooth one, but serious injuries were rare. Although mortality and injury rates to fish after passage over the spillway models were typically low, higher cumulative rates from passage over many diversions indicates managers should use structures that reduce injury and mortality rates wherever possible.

1. Introduction

Upstream and downstream movements of fishes in river systems worldwide have been altered by placement of instream dams and diversions that prevent or reduce passage or cause injury and mortality (Dynesius and Nilsson, 1994; Gehrke et al., 2002; Nilsson et al., 2005; Larinier, 2008; Katopodis and Williams, 2012). Efficacy of various passage structures to enhance upstream movements of fish have been extensively studied, especially for adult life stages of anadromous salmonids (reviews by Roscoe and Hinch, 2010; Katopodis and Williams, 2012), and research on upstream passage by small-bodied non-salmonid fishes has recently increased (Bestgen et al., 2010; Dockery et al., 2017). In contrast, effects of downstream fish passage over water diversion structures, particularly for non-salmonid or early life stages of fishes, has received less attention (Coutant and Whitney, 2000; Pavlov et al., 2008; Katopodis and Williams, 2012; Williams et al., 2012). Research has lagged mainly because initial efforts focused on re-establishing upstream fish passage with less consideration of downstream passage effects (Larinier and Travade 2002).

Downstream fish passage investigations have focused relatively narrowly on larger-bodied (usually > 100 mm total length, TL) juvenile salmon at large and relatively high hydroelectric dams, mostly in western North America. Instream structures may delay or prevent downstream movements, damage fish passing over spillways or through hydroelectric facilities, cause increased predation by other fish and birds either upstream or downstream of structures, or induce changes in dissolved gas concentrations in water that injure fish. Specific mechanisms increasing mortality of fishes passing over or through structures include gas supersaturation below dams, fish collisions with hard surfaces, shear stresses, or abrupt pressure changes (Bell and DeLacy,

* Corresponding author.
E-mail addresses: kbestgen@colostate.edu (K.R. Bestgen), bmefford.co@gmail.com (B. Mefford), bobby.compton@wyo.gov (R.I. Compton).

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1972; Ruggles, 1980; Bell, 1981; Ruggles and Murray, 1983; Hackney, 1986; Larinier and Travade 2002; Clay, 1995; Northcote, 1998; Mathur et al., 1999; Schilt, 2007; Williams et al., 2012; Duncan et al., 2017). Effects of downstream fish passage over smaller, low-head diversion dams are poorly understood, but are potentially important because over 75,000 structures 2-m or higher exist in the US alone, including > 19,000 in the Great Plains region (Fausch and Bestgen, 1997; Graf, 2006; Agostinho et al., 2007; Perkin et al., 2015). Successful dam passage in both upstream and downstream directions (two-way permeability) is needed for instream structures to be compatible with resident fishes that require stream connectedness.

Downstream passage of fish over low-head diversion dam spillways has been assumed relatively benign (Larinier, 2008; Katopodis and Williams, 2012), although there is only scant literature to substantiate that claim, especially for warmwater fish taxa that are small-bodied (e.g., < 50 mm total length [TL]). In general, survival and injury rates of fish passed over structures may be mostly dependent on the manner in which energy is dissipated in the spillway, and the associated potential for fish strikes (Larinier and Travade, 2002). Thus, smooth spillways, a common design for irrigation diversions, may be less injurious to aquatic life, than a structure with many energy dissipation structures. Similarly, free overfalls that spill into an obstruction-free stilling basin are considered benign because small-bodied fish do not achieve terminal fall velocities required to cause injuries when entering the water (summary in Larinier and Travade, 2002). There is recent renewed interest in stepped spillway construction because of construction innovations over earlier designs (Chanson, 2002) and for increased aeration (Baylar et al., 2006; Aras and Berkun, 2010). However, effects of stepped spillways on fish passing downstream are less well-known and likely less fish-friendly because of increased strikes on energy dissipation steps (Boes and Hager, 2003; Baylar et al., 2006). Regardless of spillway type, fragile and weak swimming small-bodied fish may be susceptible to injury during downstream passage over spillways. Mortality may be especially high in areas where multiple diversion spillways exist, leading to high cumulative mortality, even if effects from a single dam are relatively low. Understanding those cumulative effects requires information on survival and injury rates of small-bodied fishes passing over various spillway designs.

To remedy that information gap, we measured mortality and injury rates for early life stages of fathead minnow *Pimephales promelas* (family Cyprinidae), hybrid rainbow trout *Oncorhynchus mykiss* X cutthroat trout *O. clarkii* (family Salmonidae, hereafter called trout), and razorback sucker *Xyrauchen texanus* (Catostomidae) after passing over three commonly used spillway structures (Larinier and Travade, 2002). These included a free-overfall spillway with an unsupported jet that freely impinges into the stilling basin (Fig. 1), an ogee-shaped spillway with a smooth surface (smooth spillway), and an ogee-shaped spillway with energy dissipation steps (stepped spillway) (Fig. 2, showing stepped spillway schematic; smooth spillway was identical except without steps). The taxa used in this study represent globally wide-ranging families in cold- and warm-water streams and should be reasonable proxies of the diversity of body size and morphology of small-bodied fishes where downstream diversion dam passage effects are of interest. Increased knowledge of mortality and injury to fish from downstream passage, information that is scant in the literature, will focus conservation actions related to diversion dam effects on stream fish assemblages.

2. Materials and methods

2.1. Test species

We used fish species in globally widespread fish families to increase the generality of our results. Because differences in fish size may affect fish behavior, swimming speed, and mortality and injury rates, we used small and large size-classes, nominally defined in this study as having mean total length [TL] of 25 and 50 mm, respectively, for fathead minnow and trout and small razorback sucker in each spillway and experimental condition. Mean length of small fathead minnow, trout, and razorback sucker used in experiments was 22.8, 27.4, and 25.0 mm TL, respectively. Mean length of large fathead minnow and trout used was 44.7 and 51.8 mm, respectively. Thus, sizes of fish corresponded closely to nominal small and large size categories, which were subsequently used as class variables in statistical analyses rather than actual fish sizes.

2.2. Model testing, survival, and injury studies

Experiments were conducted at the U.S. Bureau of Reclamation, Water Resources Research Laboratory, Denver, CO. Fish were acclimated to test temperatures (16–18 °C) over a period of several hours prior to release. The free-overfall spillway test apparatus was a 15-cm diameter pipe with an 8.8-cm-wide rectangular nozzle positioned 5.7 m above the tailwater. Spillway height was about that of an existing ogee-shaped spillway model in the laboratory, and seemed a reasonable approximation of the height for structures used in the field, based on field observations of the authors. All free-overfall spillway tests were conducted with a flow of 7.1 *L*/s (0.023 m^3/s). Test discharge simulated a free-overfall flow per unit width of 0.08 $m^3 \cdot s^{-1} \cdot m^{-1}$ (flow per unit width, or m^3/s measured across a 1-m width) at a brink depth (flow

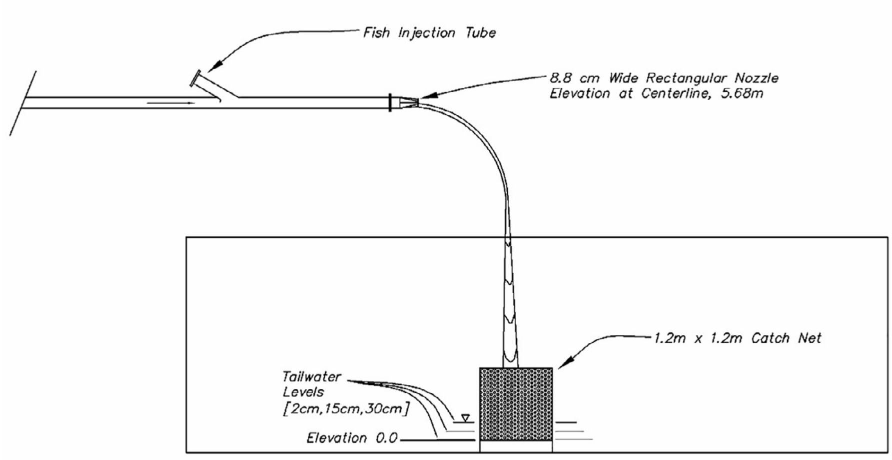

Fig. 1. Free-overfall spillway model test apparatus.