Evaluating the effects of an electric barrier on fish entrainment in an irrigation canal in Colorado

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Abstract

Entrainment of fish in irrigation canals is a source of mortality for sport and native fishes and can affect populations and species diversity. To reduce entrainment of wild trout, an electric barrier was installed on the South Canal, an irrigation ditch on the Gunnison River in western Colorado, USA. The objective of this study was to evaluate the effectiveness of the barrier by marking fish upstream of it and estimating fish populations in the canal downstream before and after the barrier was operational. Three groups of fish were tagged and released upstream of the barrier: fish from the canal, wild fish from the Gunnison River, and hatchery-reared Rainbow Trout. Boat electrofishing was completed in the canal reach below the barrier, and population estimates were made with the Huggins Closed Capture Model. The estimated Brown Trout population of the canal declined following the installation of the barrier, but Rainbow Trout remained stable because of the entrainment of small fish and their growth and survival in the canal. A total of 288 tagged fish less than 300 mm and 4 fish greater than 300 mm were recovered below the barrier, representing 1.3% of all tagged fish. The electric barrier appears to successfully exclude a portion of adult-sized trout from the irrigation canal, but smaller adult and sub-adult trout can pass the barrier. The entrainment, growth, and survival of smaller fish maintain a reduced but stable population of fish in the canal, but fewer entrained mature fish is likely a benefit to the populations of the Gunnison River.

KEYWORDS

Colorado, fish barriers, fish deterrents, fish entrainment, irrigation canals

1 | INTRODUCTION

Many freshwater fishes must migrate substantial distances to fulfill specific life history requirements such as feeding, reproduction, and developmental growth (Schlosser, 1991). The ability to move within large river systems and their associated tributaries is vital for salmonid species like Rainbow Trout and Brown Trout which are known to move long distances and have diverse life histories (Behnke, 2002). Habitat connectivity is important for different life stages of stream fishes that use a diverse range of habitats (Fausch, Torgersen, Baxter, & Li, 2002). Construction of dams and water diversions can reduce that connectivity and fragment lotic ecosystems, fundamentally changing a river’s temperature and flow regimes as well as nutrient cycles and sediment transport (Ward & Stanford, 1979). Additionally, dams and irrigation diversions are often a direct source of mortality to fishes that may reduce populations and impact biodiversity (Carlson & Rahel, 2007; Moyle & Williams, 1990).

Fish entrainment in irrigation canals is a large problem in the western United States and worldwide (Carlson & Rahel, 2007;
Clothier, 1953; Kaeding & Mogen, 2020; Moyle & Williams, 1990; Roberts & Rahel, 2008). The loss of fish in irrigation canals has been shown to be a population sink for trout in Wyoming (Roberts & Rahel, 2008). Because of the limited swimming ability of juvenile fish, they are often disproportionately affected by water diversions, especially during high flow periods (Hooley-Underwood et al., 2018). Water use in the western United States and the associated infrastructure is expected to increase in the future because of both population growth and a declining water supply related to climate change, further fragmenting aquatic habitats (MacDonald, 2010).

Fish deterrent systems can guide fishes away from sources of mortality such as hydropower turbines and irrigation canals but are also used to limit the spread of invasive species (Jones et al., 2021; Noatch & Suski, 2012). There are two main types of fish deterrent systems: physical barriers, and nonphysical (behavioral) guidance. Physical barriers include screens, netting, drop structures, and low-head dams (Noatch & Suski, 2012). Nonphysical guidance barriers use external stimuli to influence fishes’ behavior to divert them from unwanted areas and includes electricity, strobe lights, acoustic deterrents, air bubble curtains, water velocity, chemical deterrents, pheromones, and magnetic fields (Jones et al., 2021; Noatch & Suski, 2012). Both physical and behavioral fish guidance systems have been successful in excluding fish from unwanted areas but they have different costs and benefits that are generally site dependent and highly variable (Kim & Mandrak, 2019).

The South Canal in southwest Colorado diverts an average of 444,793,557 m3 (360,600 acre-feet) of water each year from the Gunnison River for irrigation and municipal use in the surrounding Uncompahgre Valley. The Gunnison River below the South Canal is a sixth-order stream with pool-riffle or pool-riffle/planform bed morphology in the Rocky Mountains. It has a mean annual discharge of 35.4 m3/s and a drainage basin area of 1605 ha.

From the diversion structure and barrier, the canal travels underground 9.2 km through the Gunnison Tunnel before emerging approximately 800 m above the hydropower plant (Figure 1). There is a total of 12.4 km of earthen canal which contains the majority of fish that are entrained from the Gunnison River. The canal diverts water from March through November each year, with the amount of water depending on water supply and irrigation demand. During winter months, the canal is generally shut off with only a very small amount of flow as a result of accretions and seepage. About twice per month, it is partially opened to run approximately 2.8 m3/s through the canal for 24–48 hr to fill a drinking water supply reservoir. Because of low and intermittent flows in the canal, fish survival over winter was thought to be low but variable year to year depending on frequency of freezing temperatures. However, in the winter of 2012–2013 there was a constant discharge of 0.6–0.7 m3/s to keep water supply reservoirs full during construction of the hydropower plant. This resulted in what appeared to be a much larger number of fish in the canal in spring of 2013 due to increased survival of entrained fish.

### 2.2 Electric fish barrier

The fish barrier was constructed in 2012 and was operational before the 2013 irrigation season. It consists of a series of vertically suspended electrodes across the east portal of the Gunnison Tunnel. The waterway at the barrier is 22.6 m wide, 4.9 m deep, and has water velocities between 0.2 and 0.7 m/s and conductivity generally less than 300 μS/cm. The system is powered by three Smith-Root 1.5 KVA pulsators with a maximum power output of 4.5 kW and is designed to operate with a frequency of 2 Hz, a pulse width of 0.005 s, and a field strength of 0.4 V/cm. The barrier was designed to exclude “brood stock” Rainbow and Brown Trout but the target size was not specified (Smith-Root, 2011). The barrier is believed to have operated continuously as planned throughout the entire 2013–2014 irrigation seasons. Communication has been lost for brief time periods (i.e., 6 out of over 6000 hr of operation in 2013) but operation of the barrier was thought to be unaffected, and it is assumed that is has functioned continuously during the irrigation seasons of the last 2 years of the study (J. Heneghan, personal communication, February 3, 2015).

The study reach was downstream of the west portal of the canal, just below the first drop structure and hydropower plant (Figure 1). The reach was 1.2 km long, ending at the second concrete drop structure (UTM NAD83 Zone 13, 258703, 4262335). The wetted width of the canal averaged 14.1 m with a discharge of 0.6–0.7 m3/s in March 2013. The wetted width averaged 21.4 m in October 2013 with a discharge of 15.3 m3/s. The study reach represents 9.4% of the total...
earthen portion of the South Canal. While fish routinely pass through the high-velocity concrete portions of the canal, the majority of fish reside in the lower gradient earthen portion of the canal. The study reach, while representative of the earthen sections of the canal, contains an unknown proportion of the total entrained fish. Fish in the study reach must have passed the electric barrier, navigated the 9.2 km tunnel, avoided entrainment in two small lateral canals, and survived the passage through the hydropower turbines to be detected by our sampling in the canal.

2.3 | Tagged fish

Four groups of fish were tagged and released in the Gunnison River upstream from the South Canal diversion. One hundred and twenty-five fish (59 Brown Trout and 66 Rainbow Trout) from the March 2013 sampling of the stilling basin were moved from below the barrier to above and received both coded wire tags (CWTs) and adipose fin clips. Mean length of the tagged fish was 241 mm for Brown Trout (range 165–310 mm) and 232 mm for Rainbow Trout (180–392 mm). Wild fish were captured by boat electrofishing in the Gunnison River above the barrier on June 17 and 19, 2013, and tagged with both CWTs and adipose clips. A total of 1265 fish were tagged (653 Rainbow Trout and 612 Brown Trout). The mean length of Brown Trout was 281 mm (103–737 mm) and that of Rainbow Trout was 336 mm (82–547 mm). Hatchery-reared fingerling Rainbow Trout (19,800 fish with a mean length of 68 mm) were marked with CWTs on June 24–26, 2013 and stocked into the Gunnison River 1.1 km above the barrier on July 26. In 2014, the focus was on tagging larger fish, and 1841 wild fish from the Gunnison River (mean total length 396 mm, range 200–545 mm) collected above the barrier were tagged with 32-mm half-duplex PIT (passive integrated transponder) tags. A mark-recapture population estimate was made during the tagging effort (same equipment and techniques utilized for other estimates) and an estimated 21.7% of the fish larger than 200 mm in the Gunnison River above the barrier were tagged in 2014. With all tagging efforts combined, a total of 23,031 trout ranging from 65 to 737 mm in total length were tagged and released into the Gunnison River above the barrier.

2.4 | Fish population estimates

The South Canal was sampled with mark-recapture electrofishing (October 2011, October 2013, and October 2014) and multiple-pass removal (March 2013) to estimate fish populations of adult and juvenile trout. The study reach for all three occasions was the same, but different sampling methods were used in March 2013 because of the
starkly different size of the canal during and after the irrigation season (14.2–25.5 m$^3$/s vs. 0.6–0.7 m$^3$/s).

In March 2013, the canal was sampled to estimate the number of fish in the study reach before the barrier was operational and to reduce the numbers of fish as much as possible. Discharge was 0.6 m$^3$/s and the canal consisted of two distinct habitat types, the concrete stilling basin and the earthen portion of the canal below, so the two areas were sampled independently. The entire stilling basin was sampled with a bag seine that was 15.2 m long and 1.8 m deep with 0.3175 cm mesh. Multiple seine hauls were made through the stilling basin so a multiple-pass removal population estimate could be made (Anderson, Burnham, & Otis, 1982; Zippin, 1958). Fish were held in a live pen and then measured for total length to the nearest millimeter. The portion of the canal below the stilling basin consisted of a shallow, slow-moving channel that was 1.1 km long and averaged 14.1 m wide. A sampling reach was randomly chosen in this portion of the study area that was 304.8 m long and block nets were used to ensure closure to satisfy the assumptions of the multiple-pass removal model (Anderson et al., 1982). Five Smith-Root LR24 backpack electrofishers were used to complete a two-pass removal population estimate. Fish were held in a live pen and measured to the nearest millimeter, and weighed to the nearest gram. After the March 2013 estimate was complete, all fish captured were removed from the canal in an effort to reduce fish numbers in the study reach before the barrier's first season of operation. To estimate the total trout in the study reach in March 2013, the two-pass removal electrofishing estimate was expanded for the length of canal that contained similar habitat and added to the removal estimate from seine hauls for the stilling basin. The final population estimate for fish in March 2013 was computed by subtracting the 876 salvaged fish from the combined population estimate.

Mark-recapture population estimates in the canal were conducted on October 2011, October 2013, and October 2014 with a 4.3 m aluminum jet boat with a Smith-Root 2.5 GPP electrofisher. The study reach, equipment, and methods for all occasions were the same. Fish were measured to the nearest millimeter and all fish on the recapture pass were weighed to the nearest gram. All captured fish were examined for adipose fin clips and checked for CWTs with a Northwest Marine Technology T-Wand Detector and for PIT tags with an Oregon RFID handheld reader. On the marking pass, all fish greater than 150 mm were marked with a caudal fin punch and held in a live pen to ensure recovery. Fish were returned throughout the study reach by boat to ensure redistribution in the population. The recapture event was completed 72 hr after fish-marking, and the interval between capture events was chosen to maximize redistribution of marked fish throughout the population but to attempt to meet demographic and geographic closure assumptions of the model (Curry, Hughes, McMaster, & Zafft, 2009). The hydropower plant served as an upstream migration barrier that further ensured geographic closure.

Because population estimates made through electrofishing are commonly biased because of size selectivity of the gear, we took measures to ensure robust estimates (Riley & Fausch, 1992; Saunders, Fausch, & White, 2011). The data were analyzed in Program Mark with the Huggins Closed Capture Model (Huggins, 1989; White & Burnham, 1999). Capture probabilities were modeled with length as an individual covariate, similar to the approach described in Saunders et al. (2011). Four models were built by estimating capture probabilities using length, species + length, as well as a constant capture probability for all fish, identical to a Lincoln Petersen model (Seber, 1982). Akaike's information criterion corrected for small sample size (AICc) was used to rank model performance. To account for model selection uncertainty, population and parameter estimates were made by averaging AICc weights across all four models (Burnham & Anderson, 2002). To compare fish population estimates from different years, we computed estimates and 95% confidence intervals with Program Mark. Statistical significance was evaluated at the $\alpha = .05$ level by determining if an estimate fell within the 95% confidence interval of another estimate.

3 | RESULTS

3.1 | Fish population estimates

In October 2011, there were an estimated 2994 ± 1043 total fish in the South Canal study reach. In the spring of 2013, there were an estimated 1583 ± 70 fish in the study reach (89% in the stilling basin). Eight-hundred and seventy-six of these fish were removed from the study reach, leaving an estimated 707 fish when the irrigation season began in the spring of 2013. In October 2013, the estimated population had increased to 1764 ± 279 trout. The population estimate of total fish in the study reach decreased from October 2011 to 2013 but that difference was not statistically significant at the $\alpha = .05$ level due to the uncertainty around the 2011 estimate related to higher flows and lower capture probability. Subsequent sampling occasions had much higher capture probabilities, generally in the 20% range (0.11–0.33). In October 2014, the study reach contained 1900 ± 379 fish. Brown Trout were more numerous than Rainbow Trout in the canal and their density decreased over time while number of Rainbow Trout fluctuated but remained generally stable (Table 1). The increase in fish by 1056 in the canal from March 2013 to October 2013 is evidence for fish successfully passing the barrier and surviving the turbines. The size structure and species composition of fish in 2013 also provide evidence of fish entrainment, specifically for Brown Trout (Figure 2).

The analysis of the mark-recapture data indicated that modeling capture probabilities by fish length was important in the South Canal to get robust population estimates (Table 2). The exception was the March 2013 sampling, when the canal contained a lower number of fish and there was little variation in fish size after they had overwintered in an intermittent canal (Figure 2). Then, a simple removal model with constant capture probability was favored, but models containing fish length still had 27% of the model weight. Modeled capture probabilities for the mark-recapture electrofishing estimates increased with fish size. For example, in October of 2014 the estimated capture probability of a 400 mm fish was approximately 2.9 times that of a
200 mm fish (0.37 vs. 0.13). Estimates using length to model capture probabilities were 23% higher (6–41%) than estimates from a simple Lincoln–Petersen model, and models containing length as a covariate had between 98% and 100% of the model weight across all sampling occasions. Our data support earlier findings that modeling capture probabilities by length is important for making unbiased fish population estimates with electrofishing.

### 3.2 Tagged fish

In October 2013, after the first irrigation season in which the electric barrier was in use, a total of 248 CWT fish from 123 to 337 mm were documented passing through the barrier: mostly smaller hatchery-reared Rainbow Trout \((n = 246, \text{mean length } 163 \text{ mm, in October, Figure 3})\). Only two Brown Trout were confirmed passing the barrier (310 and 337 mm) and no adult-sized Rainbow Trout. No tag loss was observed: all of the larger fish were double-marked, and no fish were observed with an adipose clip but without a CWT. It is unknown exactly when or what size of all the tagged fish in 2014 passed the barrier because fish lived and grew in the canal throughout the study. The 2013 data give the best indication of the size of fish that passed the barrier because they were in the canal for a maximum of 7 months. The CWT Rainbow Trout could have passed the barrier as small as 68 mm early in the irrigation season and then survived to be captured at a larger size or could have passed the barrier as large as the 163-mm average length observed in the October sampling.

Overall, 1.17% of all the tagged fish in Gunnison River were captured in the study reach in 2013. The CWT stocked Rainbow Trout represent 1.24% of the marked fish in the Gunnison River and only 0.30% of the tagged wild Brown Trout were recovered in the study reach. The population estimate of only the CWT Rainbow Trout in the study reach was 1486 ± 768, representing 7.51% of the tagged fish released into the Gunnison River above the barrier.

In 2014, 44 tagged fish were encountered in the canal: 40 of the hatchery-reared Rainbow Trout (mean length 326 mm at the time of capture) and 4 CWT and fin-clipped wild Rainbow Trout (296–398 mm). By the end of the study, 288 small or medium-sized fish had been documented passing the barrier. Only four fish >300 mm and no fish >400 mm were documented passing the electric barrier. Less than 2% of all tagged fish were recovered in the canal study reach in 2 years, the majority being the smaller stocked Rainbow Trout.

### Table 1 Fish population estimates and 95% confidence intervals from the South Canal 2011–2014

| Date         | Species          | Population estimate |
|--------------|------------------|---------------------|
| October 2011 | Brown Trout      | 2359 ± 981          |
|              | Rainbow Trout    | 634 ± 354           |
| March 2013   | Brown Trout      | 412 ± 52            |
|              | Rainbow Trout    | 295 ± 46            |
| October 2013 | Brown Trout      | 1035 ± 150          |
|              | Rainbow Trout    | 728 ± 235           |
|              | Stocked CWT Rainbow | 1486 ± 768   |
| October 2014 | Brown Trout      | 964 ± 258           |
|              | Rainbow Trout    | 936 ± 278           |
|              | Stocked CWT Rainbow | NA                |

### Discussion

The electric barrier on the South Canal appears to serve its designed purpose of excluding larger fish from the irrigation system. Some fish in the Gunnison River are successfully passing the electric barrier and surviving the turbines, mostly smaller fish. Their growth and survival in the canal maintains a stable fish population that is significantly lower than before the barrier for Brown Trout \((\alpha = .05)\).
Many smaller marked fish were documented passing the electric barrier but few large fish, and operation of the electric barrier led to a decline in the number of fish in the South Canal. The canal contained approximately 1094 fewer fish in October 2014 at the conclusion of the study than in October 2011, before the erection of the barrier. While the total fish estimates in the canal have declined since the barrier was installed, there is no significant difference at the $\alpha = .05$ level, primarily due to the low capture probability and corresponding high uncertainty around the October 2011 estimate. The number of Brown Trout was significantly lower in 2014, that is, 2 years after the barrier was installed, while the number of Rainbow Trout has remained relatively stable. Large numbers of smaller fish have been shown to pass the barrier, as evidenced by both the number of marked fish and the stable trout population in the canal after the barrier was operational. This differential effect related to fish size was expected with electrical-based fish deterrence and reflects the established effects of pulsed DC current on fish in both deterrence and electrofishing (Noatch & Suski, 2012; Riley & Fausch, 1992).

The lack of a significant decline in the Rainbow Trout populations in the canal after the barrier is likely related to entrainment of small fish and higher than expected survival and growth of fish living in the canal. In 2014, 17% of all sampled fish (37% >350 mm) had been handled the previous October, denoted by the presence of a healed caudal punch scar. This indicates that there is fair to good overwinter survival in the canal. Growth of fish living in the study reach is also relatively high; CWT Rainbow Trout grew an average of 163 mm from age-1 to age-2. With high growth rates and annual survival, the large numbers of smaller fish that pass the barrier maintain a relatively stable population of fish in the study reach, even though large fish do appear to be excluded from the canal by the electric barrier.

The difference between species is likely due to two factors: larger size of age-0 Brown Trout when water is being diverted, and the potential spawning of Rainbow Trout in the study reach. Because

| TABLE 2: Model selection results for fish population estimates in the South Canal, 2011–2014 |
|-----------------------------------------------|------|-----|-----|-----|
| October 2011 (Mark recapture)                |     |
| Model                                         | AICc | K   | $\Delta$AICc | wi  |
| Time + length                                 | 893.0| 3   | 0             | 0.75|
| Time + species + length                       | 895.4| 5   | 2.4           | 0.23|
| Time                                          | 900.3| 2   | 7.3           | 0.02|
| Time + species                                | 902.7| 4   | 9.7           | 0.01|
| March 2013 (Two-pass removal)                 |     |
| Model                                         | AICc | K   | $\Delta$AICc | wi  |
| Constant capture $p$                          | 117.4| 1   | 0             | 0.53|
| Species                                       | 119.3| 2   | 1.9           | 0.20|
| Length                                        | 119.4| 2   | 2.0           | 0.20|
| Length + species                              | 121.3| 3   | 3.9           | 0.07|
| October 2013 (Mark-recapture)                |     |
| Model                                         | AICc | K   | $\Delta$AICc | wi  |
| Time + species + length                       | 1760.5| 5  | 0             | 0.77|
| Time + length                                 | 1762.8| 3  | 2.38          | 0.23|
| Time + species                                | 1779.0| 4  | 18.58         | 0.00|
| Time                                          | 1787.2| 2  | 26.72         | 0.00|
| October 2014 (Mark-recapture)                |     |
| Model                                         | AICc | K   | $\Delta$AICc | wi  |
| Time + length                                 | 1107.0| 3  | 0             | 0.88|
| Time + species + length                       | 1110.9| 5  | 3.9           | 0.12|
| Time                                          | 1122.7| 2  | 15.7          | 0.00|
| Time + species                                | 1126.7| 4  | 19.8          | 0.00|

Note: Included are Akaike information criterion corrected for small sample size (AICc), the number of model parameters (K), the difference in AICc values ($\Delta$AICc), and model weight (wi).
Brown Trout fry in the Gunnison emerge about 8–10 weeks earlier than Rainbow Trout, they are larger during their first summer (Nehring & Anderson, 1993). Because the barrier is size selective, Brown Trout fry are expected to be entrained at a lower rate than Rainbow Trout. The canal is first filled with water around April 1 of each year, just before Rainbow Trout spawn. Large numbers of age-0 Rainbow Trout were observed in the canal in July 2014. It is unknown if they were entrained fish from the Gunnison River or were spawned in the canal; both are likely. Brown Trout spawn throughout the month of October in the Gunnison River, and flows in the canal generally cease at the end of that month, with subsequent winter flows being intermittent. There is minimal, poor-quality spawning habitat for Brown Trout in the canal compared to that of Rainbow Trout, which spawn at higher flows in the canal that are stable or increasing. A combination of higher entrainment rates and better potential spawning success in the canal likely leads to higher numbers of small Rainbow Trout in the canal.

In this study, we estimated the minimum number of fish that passed the barrier, navigated the 9.2 km tunnel, avoided entrainment in two small lateral canals, survived passage through the hydropower turbines, and were detected in the sampling reach. We can expand those estimates to get an idea of total entrainment rates, but more continuous monitoring would be required to get a true estimate of the total number of entrained fish. If the density of fish in the study reach is representative of the rest of the canal, then an estimated 15,809 CWT Rainbow Trout fingerlings would have been entrained, or 79.8% of those fish. Only 3.2% of the larger marked wild Brown Trout in 2013 would have been entrained in the canal, probably a minor loss to the population of the Gunnison River and insignificant biologically. These are likely overestimates of the total number of entrained fish because the study reach may have a higher density of fish than the other reaches of the canal, but it demonstrates the potential extent of fish entrainment. While estimating robust entrainment rates with the barrier was not possible in this study, the true rates are likely between these minimum and maximum values: 8%–80% for small Rainbow Trout and 0.3–3.2% for larger Brown Trout. Using the 2014 population estimate, if the sampling reach is representative of the entire canal, an estimated 20,209 ± 4034 trout could be being entrained in the canal annually.

If the electric barrier on the Gunnison Tunnel is successfully excluding most fish >300 mm, then it protects approximately 15% of the trout >150 mm and 26–71% of sexually mature fish based on 2013 data from the Gunnison River. Low numbers of age-2 fish in the Gunnison are sexually mature (mostly males), while most age-3 fish are mature (Gardinio, Colorado Parks and Wildlife, unpublished data). So while the barrier is generally meeting its design objective, it is not protecting all of the sexually mature fish from entrainment. Excluding higher proportions of small trout from downstream passage is likely to be difficult and will depend on several factors including the voltage gradient of the barrier and the approach velocities of the water. However, excluding more of the adult fish is a reasonable expectation for the barrier with some operational changes. Better use of biological data of the fish populations could help improve the site-specific performance of fish barriers, as both irrigation diversions and fish populations in rivers they divert from are unique.

The results of this study agree with those of other work, indicating that the effects of electric barriers (like electrofishing) is related to fish length as well as site-specific characteristics such as water velocities (Pugh, Monan, & Smith, 1970). The probability of deterring small salmonids with an electric barrier in that study decreased with increasing water velocity, and deterrence was not practical in velocities above 0.3 m/s. The approach velocities at the South Canal barrier varied between 0.21 and 0.70 m/s in October 2011 when the discharge of the tunnel was 20.7 m³/s and of the river below the tunnel was 16.4 m³/s. Improved deterrence of small trout should be possible under these conditions with operational adjustments, but further monitoring of approach velocities at various discharges is needed.

Like water velocity, the strength of the electric field influences the effectiveness of electric barriers in deterring fish. The field strength of the South Canal barrier is currently about 0.4 V/cm, which is relatively conservative compared to some barriers (Burger, Parkin, O’Farrell, & Murphy, 2015; Raymond, 1956) but at a level that can affect the behavior of Rainbow Trout (Kim & Mandrak, 2019). Several other downstream-oriented electric barriers have utilized voltage gradients as high as 3.0 V/cm or are graduate-field fish barriers where several rows of electrodes produce increasing voltage gradients between 0.2 and 1.2 V/cm (Burger et al., 2015; Raymond, 1956). The graduate-field technology appears more effective in deterring downstream movement of fish but was not feasible at the Gunnison Tunnel due to site-specific conditions. Diverting downstream moving fish is one of the more difficult applications of electric fish barriers (Burger, Parkin, O’Farrell, Murphy, & Zelgis, 2012). While achieving complete deterrence of all fish is unlikely in scenarios like the Gunnison Tunnel, reducing entrainment as much as feasible within the constraints of the system should be the objective. More research is necessary to determine whether increasing the voltage gradient, or other operational changes, at the Gunnison Tunnel barrier could improve performance on smaller fish.

Fish entrainment in the South Canal of the Gunnison River has been reduced but not eliminated by the electric fish barrier. Large numbers of smaller trout (~20,209 annually) continue to be entrained in this canal and water diversions on other rivers are likely causing similar effects. On the Colorado River in west-central Colorado, 255,338 entrained native fish were salvaged from the Government Highline Canal from 2007–2018 (Crowley & Ryden, 2019). The diversion for this canal has a physical barrier (mechanical fish screen) but it still entrains a large number of native fish, an average of 23,207 fish annually. The screens are operated when feasible through the irrigation season (March–November), although stream flows, debris, and other concerns interrupt operation (Upper Colorado River Endangered Fish Recovery Program, 2012). In Wyoming, it was estimated that between 6300 and 10,400 fish encompassing 10 species were entrained in a single canal system (Roberts & Rahel, 2008). These three examples of large irrigation diversions represent a small fraction of diversions across the west and display not only the large magnitude...
of fish entrainment that can occur but also the lack of information on the problem overall.

With over 16,000 active irrigation ditches in Colorado and the documented loss of native and sport fish in various locations, the problem of fish entrainment appears to be widespread and potentially of large magnitude in some rivers. Screening canals with mechanical or electric barriers appears to reduce the entrainment but not eliminate it. Success depends on site-specific factors, the design of the barrier, as well as its maintenance and operation. Further research is necessary in Colorado and across Western United States to document the extent of fish loss in irrigation canals and identify solutions. Closer cooperation between the engineers designing fish barriers and the ecologists who manage the fisheries is encouraged, as the local nuances of the river environment and fish populations will dictate the ultimate effectiveness. Electric fish barriers like the one on the South Canal of the Gunnison River can help address the problem, but both site-specific approaches to fish entrainment as well as a larger, riverscape perspective of stream fish populations will be necessary to address it fully.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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