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[Article]

Irrigation Canals as Sink Habitat for Trout and Other Fishes in a Wyoming Drainage

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Abstract.—Irrigation canals can be a major source of mortality for fish in the Rocky Mountain region. Our study looked at how fish were affected by the irrigation canal system in the Smiths Fork, a tributary to the Bear River in western Wyoming. There are two native species of conservation concern in the Smiths Fork drainage: Bonneville cutthroat trout *Oncorhynchus clarkii utah* and northern leatherside chub *Lepidomeda copei*. Our objectives were to determine the relative abundance of each species within the canals and the fate of trout (Bonneville cutthroat trout and brown trout *Salmo trutta*) that enter canals. During the summer of 2003 we sampled 30 sites within the Covey Canal system, which is the largest canal system withdrawing water from the Smiths Fork. Because fish were observed to accumulate at certain spots in the canal system, we developed a sampling scheme that incorporated both random sample sites and sites known to attract fish. We estimated that between 6,300 and 10,400 fish encompassing 10 species were entrained in this canal system. The two most abundant species were speckled dace *Rhinichthys osculus* (29% of all fish) and mountain sucker *Catostomus platyrhynchus* (37% of all fish). Bonneville cutthroat trout and northern leatherside chub each comprised 2% of the total entrained fish. We implanted 30 Bonneville cutthroat trout and 13 brown trout with radio transmitters to determine whether entrained trout could leave the canal system when water levels were reduced in late summer. We found that 77% of the transmitter-implanted fish died within the canals, indicating that this system functions as sink habitat for Bonneville cutthroat trout and brown trout. Based on this mortality rate, we estimated that 120 Bonneville cutthroat trout (95% confidence interval, 75–165) and 299 brown trout (280–317) perished in the Covey Canal system during the summer of 2003.

Fisheries biologists are increasingly taking a landscape approach to the management of fish populations (Schlosser and Angermeier 1995; Fausch et al. 2002). One reason for considering management issues at larger spatial scales is our increased understanding of the importance of movement in the ecology of many stream fishes (Brown and Mackay 1995; Bunnell et al. 1998). This is especially true for species such as cutthroat trout *Oncorhynchus clarkii* that use widely separated areas within lotic systems during their life cycle (Jakober et al. 1998; Schrank and Rahel 2004; Colyer et al. 2005).

The ability of fish to move among widely separated habitats to fulfill life history requirements can be negatively affected by water development activities. For example, dams and their associated reservoirs can block upstream migration of spawning fish (Schmetterling 2003), impede downstream migrations of juvenile fish (Raymond 1979) or subject juvenile fish to increased predation (Beamesderfer et al. 1996). Canals built for water conveyance and irrigation also disrupt fish migrations when they entrain fish (Clothier 1953; Gale 2005; Post et al. 2006; King and O'Connor 2007). In many cases, water is diverted into irrigation canals only during the agricultural growing season, and thus the canals are dry and unsuitable as fish habitat for part of the year. From a landscape perspective, canals that entrap and kill fish can be considered sink habitats because they are unsuitable for reproduction or long-term survival (Pulliam 1988; Dunning et al. 1992).

Although studies have documented the entrainment of fish in irrigation canals (Clothier 1953; Leslie et al. 1990; Reiland 1997; Gale 2005; Post et al. 2006; Carlson and Rahel 2007; King and O'Connor 2007), little is known about the ability of fish to escape from canals and return to streams when the canals go dry. In natural river systems, fish species may use seasonally flooded side channels for reproduction or feeding but then return to main channel habitats as flood waters recede (Kwak 1988). By contrast, irrigation canals often have a headgate structure that may limit the movement of fish back into the main stem. Because irrigation canals are a widespread feature of the landscape in arid regions, it is important to know whether they serve as a seasonally available habitat for fish, or as a sink habitat that causes additional mortality on fish populations.

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Bonneville cutthroat trout *Oncorhynchus clarkii utah* in the Bear River drainage of Wyoming and Idaho are known to exhibit large seasonal movements associated with spawning (Schrank and Rahel 2004; Colyer et al. 2005). Bonneville cutthroat trout were unsuccessfully petitioned to be federally listed as threatened (USFWS 2001) but remain a species of conservation concern with an imperiled heritage rank of 1 within Wyoming (Keinath et al. 2003). Given the conservation status of Bonneville cutthroat trout, it is important to know if their migratory behavior results in entrainment within irrigation canals. The northern leatherside chub *Lepidomeda copei* is another species of conservation concern (imperiled heritage rank of 1 within Wyoming; Keinath et al. 2003) that is present in the drainage. Northern leatherside chub have recently been recognized as separate species, distinct from the southern leatherside chub *Lepidomeda aliciae*. This recent split has augmented the need to conserve the northern leatherside chub given that there are only four known locations of extant populations (Johnson et al. 2004). No information existed on the extent to which the northern leatherside chub might also become entrained in irrigation canals.

The objectives of our study were to (1) quantify the number of fish of all species entrained by the major irrigation canal system in the Smiths Fork drainage, a tributary of the Bear River in western Wyoming; (2) examine the spatial patterns in the distribution of entrained fish; and (3) estimate the percentage of entrained trout (Bonneville cutthroat trout and brown trout *Salmo trutta*) that perished within the canal system.

Study Site

Our study area was the Smiths Fork drainage, which originates in the Bridger-Teton National Forest and joins the Bear River near Cokeville, Wyoming (Figure 1). The area surrounding Cokeville is highly agricultural, and much of the water used for irrigation is diverted from the Smiths Fork by a system of canals. The 11 major irrigation canals and the lattice network they form in the Smiths Fork drainage create a labyrinth that could act as a sink habitat for fish.

Methods

Site selection.—Our sampling took place in the Covey Canal system. This system consists of the Covey, Mau, and Spring Creek irrigation canals which constitute over 50% of the length of all canals associated with the Smiths Fork (Figure 1). These three canals were divided into six sections based on the locations of headgates and siphon structures that we thought might be movement barriers for fish in the canals (Figure 1). The headgates were typically concrete structures placed across the channel with gates that could be raised or lowered to regulate flow under the gates and into the canals. The siphons consisted of pipes that moved water down and across valleys and then up the opposing valley wall. Although fish could pass downstream through a siphon, we felt it unlikely that fish could move upstream against the water flows in the siphon pipes. The Covey Canal had two siphon structures and was divided into three sections (Figure 1). The first section (Covey 1) went from the canal headgate to the first siphon, the second section (Covey 2) went from the first siphon to the second siphon, and the third section (Covey 3) went from the second siphon to the end of the canal in a pasture. The Mau Canal was divided into two sections: upstream (Mau 1) and downstream (Mau 2) of the only siphon in the canal. The final section consisted of Spring Creek (SP), which was a natural stream course that had been modified to convey water between the Covey Canal and the Mau Canal.

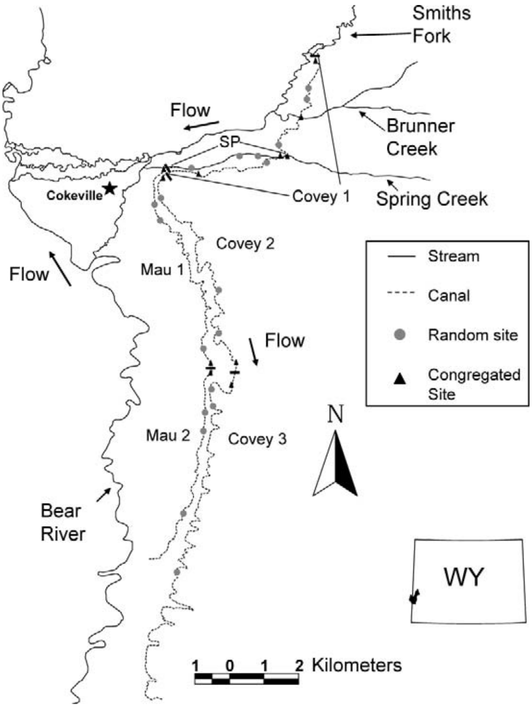

FIGURE 1.—The Smiths Fork, a tributary to the Bear River in western Wyoming, and the irrigation canals that form the Covey Canal system. Fish populations were estimated in 2003 at both random and congregated sites in the sections of the Covey Canal (Covey 1, 2, and 3), Spring Creek (SP), and the Mau Canal (Mau 1 and 2) delineated by bars.

We divided the potential sample sites in the canals into two strata: congregated and random. All sample sites were 200 m long. During preliminary sampling in the summer of 2002, we observed that fish often were concentrated at features such as headgates, natural stream crossings, and siphons. To improve our estimate of the number of entrained fish, we sampled all such sites ($n = 11$), which we referred to as the congregated stratum (Figure 1). Three of the congregated sites consisted of the 200 m directly downstream of the headgates (water intake points) for the three canals composing the Covey Canal system. Two congregated sites were located where natural stream channels intersected the Covey Canal: one at Brunner Creek and one at Spring Creek. The remaining six congregated sites were located directly upstream and downstream of the three siphon structures in the Mau Canal and the Covey Canal (Figure 1).

In addition to the 11 congregated sites, 19 random sites were sampled. Three 200-m sampling sites were randomly selected in each of the six canal sections. An additional site was allocated for Covey 1, the canal section directly downstream of the Covey Canal headgate (the main water intake structure within the Covey Canal system). This resulted in Covey 1 having a total of four, randomly selected sites. This additional site was deemed appropriate since preliminary sampling in 2002 indicated that the bulk of entrained fish in the Covey Canal system were found in Covey 1. The location of each of the random sites within the six canal sections was determined via a random selection process. We took the total length (TL) of each canal section minus the congregated sites and divided it into individually numbered 200-m sites. A random number was generated and used to select the 200-m sites to be sampled within each canal section.

Estimation of fish abundance in the Covey Canal system.—We used three-pass depletion electrofishing to estimate fish population abundance at the 11 congregated and 19 random sites in the Covey Canal system during the summer of 2003 (21 May through 1 August). We used information gained from our preliminary sampling in 2002 along with the knowledge of local canal managers when choosing our sampling period to ensure it would fall within the irrigation season. A block net was set up at the upstream and downstream end of each site, and fish were removed by a two-person crew using a backpack electrofishing unit. All fish were identified to species, a random subsample of each species was measured for TL (mm), and fish were then released. Population estimates were determined with the Burnham maximum likelihood method using Microfish 3.0 software (Van Deventer and Platts 1985).

To obtain an estimate of fish abundance in the Covey Canal based on our electrofishing efforts, we combined the estimates from the congregated and random sites using the equation

$$T = \sum_{i=1}^{11} T_i + \sum_{j=1}^{6} T_j, \qquad (1)$$

where

$$T_j = L_j \cdot y_j$$

and T_i represents the fish abundance estimate for the ith congregated site, T_j represents the fish abundance estimate for the jth canal section, L_j is the length in meters of canal section j, and y_j is the average linear fish density (fish/m) determined from the three to four sites chosen via our random selection process and sampled by depletion electrofishing. The linear fish density for each site was obtained by dividing the population estimate for each species by the length of the sample site (200 m); these three to four estimates from each random site were then averaged for each canal section.

The 95% confidence interval (CI) of the abundance estimate for the Covey Canal was calculated as the estimate $\pm$ $1.96 \cdot \mathrm{SE}(T)$, where the $\mathrm{SE}(T)$ is the square root of the variance ($\mathrm{var}[T]$) from the equation

$$\mathrm{var}(T) = \sum_{i=1}^{11} \mathrm{var}(T_i) + \sum_{j=1}^{6} \mathrm{var}(T_j), \qquad (2)$$

where

$$\mathrm{var}(T_j) = \left[\left(\frac{1}{n}\right)^2 \cdot \sum_{k=1}^{n} \mathrm{var}(t_{jk})\right] \cdot (L_j)^2 \qquad (3)$$

and

$$\mathrm{var}(x) = \left(\frac{1}{n}\right) \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad \text{(4; Zar 1984)}$$

for any variable x. In equation (2), $\mathrm{var}(T_i)$ is the variance at the ith congregated site, which was obtained by squaring the SE obtained from the population estimate based on the Burnham maximum likelihood method (Van Deventer and Platts 1985; SE was considered equal to SD since the sample size [n] was assumed to be one). For equations (2) and (3), $\mathrm{var}(T_j)$ is the variance of the jth canal section; $\mathrm{var}(t_{jk})$ is the variance of site k's estimated fish density (fish/m), which was determined by depletion electrofishing and chosen via our random selection process within canal section j; and L_j is the length in meters of the jth canal section. The number of sites sampled by depletion electrofishing within the jth canal section is given by n and was equal to 3 for canal sections Covey

2, Covey 3, Mau 1, Mau 2, and SP and 4 for canal section Covey 1.

Fate of trout entrained in the Covey Canal system.— We used radiotelemetry to track the movements of Bonneville cutthroat trout and brown trout entrained in the Covey Canal system and to determine whether entrained trout would return to the Smiths Fork when water flow into the canals was shut off. Fish for radiotelemetry were sampled from the Covey Canal system using a backpack electrofishing unit. These fish were weighed (g), measured for TL (mm), and implanted with radio transmitters in the field. We used the sheathed-needle technique (Adams et al. 1998), and after fish were anesthetized we surgically implanted transmitters anterior to the pelvic girdle within the fish's ventral body cavity (the antenna left trailing outside the body anterior to the anal vent). After surgery, fish were allowed to recuperate and were not released into the canal system until normal behavior was observed. Transmitter-implanted fish were released back into the canal section from which they were captured. This allowed for our initial distribution of transmitter-implanted fish to mirror natural trout distribution in the Covey Canal system. We also allowed a 2-week buffer period wherein any transmitter-implanted fish that died were not included in our analyses. Only one mortality occurred during this buffer period and that fish was therefore excluded from our analyses.

Two sizes of transmitters were used so that we could monitor the movements of a large size range of trout. In 2002, large trout (>445 g) were implanted with an 8.9-g transmitter (Model MCFT-3EM; LOTEK Wireless Fish and Wildlife Monitoring, New Market, Ontario), and small trout (155–444 g) received a 3.1-g unit (Model F1570; Advanced Telemetry Systems, Insanti, Minnesota). We also used two types of radio transmitters during 2003: an 8-g unit (Model F1820; Advanced Telemetry Systems) and a 3.1-g unit (Model F1570; Advanced Telemetry Systems). Radio transmitters did not exceed 2% of fish body weight to ensure that fish behavior was not influenced by the transmitter (Adams et al. 1998). The 8-g transmitters used during 2003 had mortality sensors that changed the pulse rate after 24 h of no movement to indicate inactivity and presumably death.

Transmitter-implanted fish were tracked using ground and aerial telemetry techniques. Twice each week, ground tracking was performed using a scanning receiver (Advanced Telemetry Systems), a three-element Yagi antenna, and a handheld global positioning system (GPS) unit that was rated accurate to 3 m (Garmin, Etrex Legend). Ground tracking was accomplished by walking along the canals or Smiths Fork and scanning the frequencies of implanted radio transmitters. When a transmitter was heard, efforts were made to pinpoint its location. Because only a portion of the transmitters had mortality sensors, when a transmitter without a mortality sensor was located an effort was made to observe fish movement to determine if the fish was still alive. If no movement was induced from shore, we entered the water in an effort to disturb the fish. If no movement was detected, a search for a carcass ensued. The locations of transmitters were recorded using a handheld GPS unit, downloaded using MapSource 3.02 software (Garmin Corp., 1999), and were later put into a geographical information systems format (ArcView and ArcMap 8.1; Environmental Systems Research Institute, Inc., Redlands, California) for movement analysis.

Aerial telemetry was performed by Mountain Air Research (Driggs, Idaho) using a fixed-wing aircraft equipped with three telemetry antennas (two-directional H, and one forward Yagi with a Telonics TAC-7 switch), a telemetry receiver (Telonics TR-2 with scanner), and a GPS unit (Apollo GX 55) that was rated accurate to 15 m. We concluded that the average accuracy of aerially determined locations was ±178 m of known benchmark locations on the ground (Roberts and Rahel 2005). Aerial telemetry was useful in providing a general location of fish, especially for fish that moved a great distance from their release locations. However, the locations of fish determined by aerial telemetry were verified by ground telemetry to increase the accuracy of fish locations.

Fish locations were monitored more frequently when flows were reduced toward the end of the irrigation season. Increasing the observations of the transmitter-implanted fish toward the end of the irrigation season helped us to monitor the escape attempts and movement patterns of entrained trout.

The fate of transmitter-implanted Bonneville cutthroat trout and brown trout in the canals was classified as either mortality or survival. The percentage of the transmitter-implanted fish that died within the irrigation canals provided an estimate of the extent to which entrainment in canals eventually leads to mortality for trout. Fish were considered to have survived if they returned to the Smiths Fork or remained alive and terminally entrained within the canal in isolated pockets of water after the irrigation season. Only fish whose fate could be confirmed were included in our analysis.

In the summer of 2002, four Bonneville cutthroat trout (TL: mean = 308.3 mm, SE = 21.8; weight: mean = 330 g, SE = 67.4) and 13 brown trout (TL: mean = 374 mm, SE = 20.5; weight: mean = 638 g, SE = 88) were captured within the Covey Canal system,

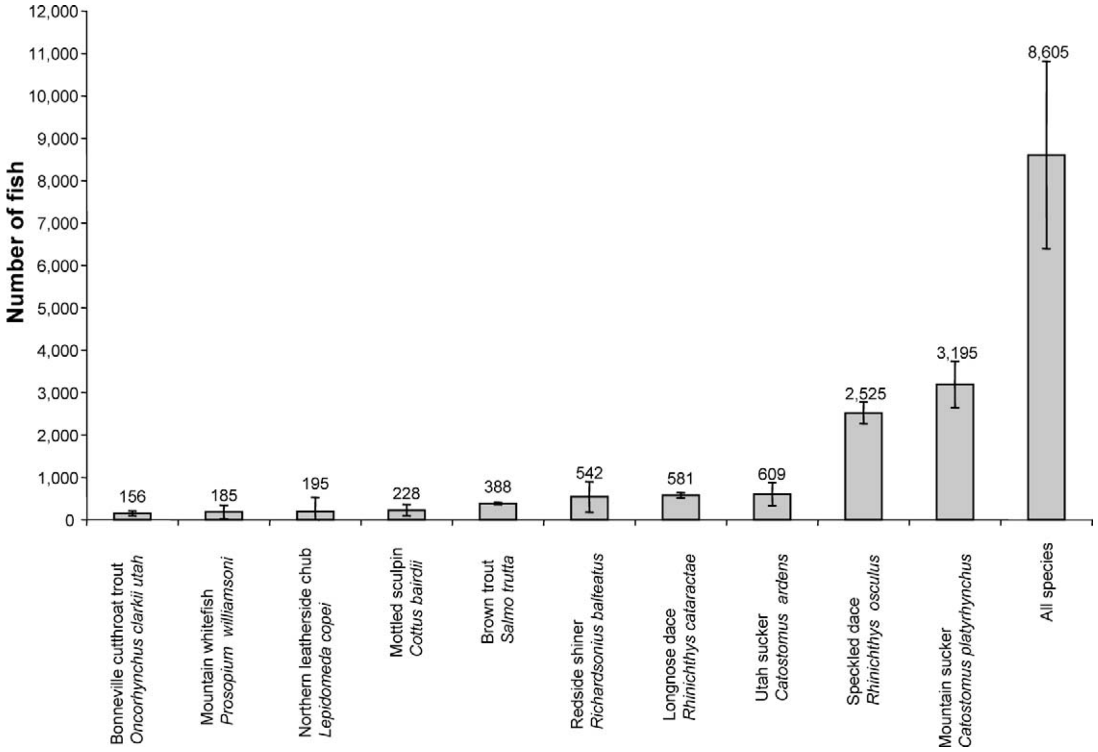

FIGURE 2.—Population estimates ± 1.96 SEs of fish species entrained by the Covey Canal system during the 2003 irrigation season.

implanted with radio transmitters, and released back into the canals. Of these fish, nine (one Bonneville cutthroat trout and eight brown trout) were released in Covey Canal section 1 and eight (three Bonneville cutthroat trout and five brown trout) were released in Mau Canal section 1. During 2003, only Bonneville cutthroat trout (TL: mean = 308 mm, SE = 10.2; weight: mean = 324 g, SE = 32.9) were implanted and released in the Covey Canal—24 were released in Covey 1, one in Covey 2, and one in Covey 3. Transmitter-implanted fish were released at their place of capture, thus allowing our distribution of transmitter-implanted fish to mimic the distribution of entrained trout throughout the Covey Canal system.

During July 2003, the headgate of the Covey Canal was monitored with an underwater video camera placed directly downstream from the headgate intake regulator to observe any movement of fish back through the headgate and into the Smiths Fork. Videotaping was done in the late afternoon until darkness prevented us from seeing fish. Images from the camera were recorded for later viewing and analysis. Individual fish approaching the headgate were counted and observed to determine if they were successful in passing upstream through the headgate structure and thus reentering the Smiths Fork.

Results

Population Estimates

We estimated that 8,605 fish (95% CI = 6,327–10,838) representing 10 species became entrained in the Covey Canal system in the summer of 2003 (Figure 2). The two most abundant species were mountain sucker, which constituted 37% of all fish, and speckled dace, which constituted 28%. The estimated number of Bonneville cutthroat trout entrained was 156 (95% CI = 97–214; 2% of all fish); brown trout, 388 (364–412; 4.5%); and northern leatherside chub, 195 (0–532; 2%).

The density of the fish in the canal system was lower the further downstream from the Covey Canal headgate a site was located (Figure 3). Congregated sites had higher linear fish densities than random sites based on a one-tailed *t*-test of log-transformed density data for all species combined ($P = 0.007$) and for trout (brown trout and Bonneville cutthroat trout) considered separately ($P = 0.02$; Figure 3).

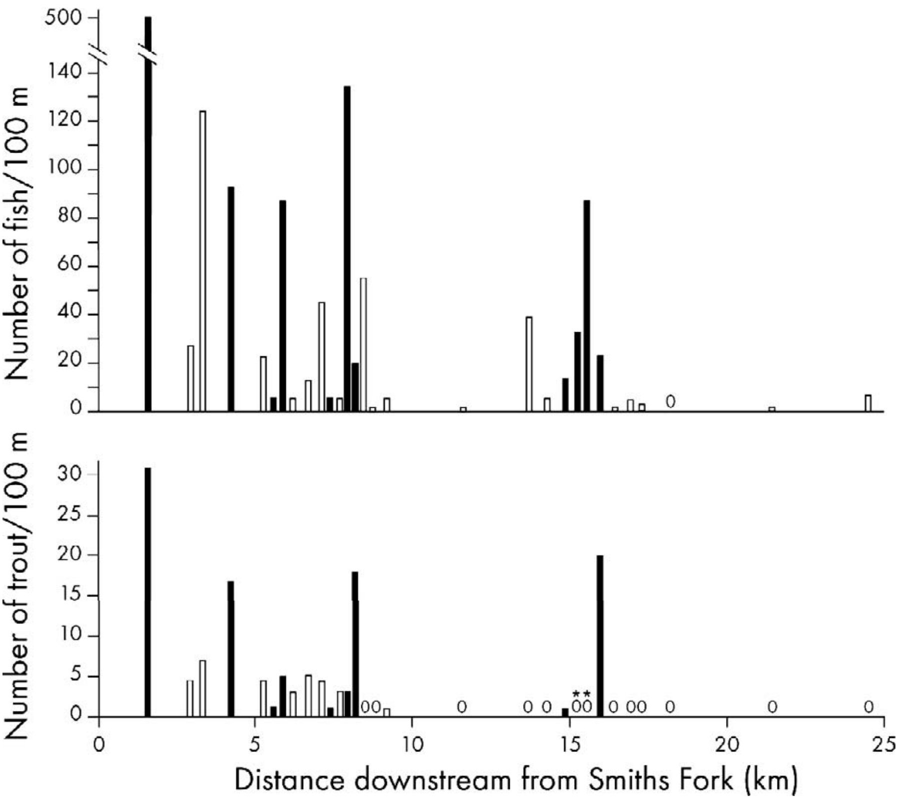

FIGURE 3.—Abundance of all species (top panel) and trout (bottom panel) in relation to the downstream locations of sites in the Covey Canal system. Fish abundances at the 11 congregated sites are indicated by dark bars, those at the 19 random sites by open bars. Zeros indicate that no trout were captured at those sites; zeros with asterisks denote the two congregated sites at which no trout were captured.

Fate of Trout Entrained in the Covey Canal System

Of the 30 Bonneville cutthroat trout that were implanted with radio transmitters and released into the Covey Canal system, 23 (77%) died within the canals, 6 (20%) escaped back to the Smiths Fork, and 1 (3%) remained alive but terminally entrained in a section of the canal that retained water at the end of the summer (Table 1). Of the 13 brown trout that were implanted with radio transmitters and released into the Covey Canal system, 10 (77%) died within the canals and 3 (23%) escaped back to the Smiths Fork (Table 1). We were able to identify escape routes for four of the nine trout that returned to the Smiths Fork. Three Bonneville cutthroat trout passed upstream through the Covey Canal headgate structure, and one Bonneville cutthroat trout returned to the Smiths Fork via Brunner Creek.

We observed 622 fish approach the headgate of the Covey Canal during 27 h of underwater video monitoring during July 2003. We could identify cyprinids and catostomids only to the family level in the videos. No Bonneville cutthroat trout, brown trout, mottled sculpin, or cyprinids were observed to pass upstream through the headgate (Table 2). The only fish to successfully pass through the headgate and return to the Smiths Fork were two catostomids. The maximum water velocity recorded directly downstream of the Covey Canal headgate was 3.2 m/s, which is near the maximum burst speed of 4.5 m/s reported for adult cutthroat trout (Furniss et al. 1991).

For the 33 transmitter-implanted fish that died in the Covey Canal system, we were able to determine the final location of all 33 transmitters; however, only 18 transmitters were actually recovered. Five transmitters were recovered near the nests of predatory birds. One transmitter, apparently still within the fish, was located in a great blue heron *Ardea herodias* as the bird flew from the canal system. We found four transmitters within carcasses of fish in remnant pools after the Covey Canal headgate had been closed, terminating water withdrawal. We recovered eight transmitters not associated with a complete carcass. At these eight recovery sites there was often evidence of predation,

TABLE 1.—Number and fate of Bonneville cutthroat trout and brown trout implanted with radio transmitters in the Smiths Fork irrigation canal system during 2002–2003.

	Bonneville cutthroat trout			Brown trout		
	Covey Canal	Mau Canal	Total	Covey Canal	Mau Canal	Total
Implanted						
Number	27	3	30	8	5	13
Mean length (mm)	309	284	278	381	336	374
Terminally entrained						
Number	1	0	1 (3%)	0	0	0 (0%)
Mean length (mm)	295					
Returned to river						
Number	5	1	6 (20%)	2	1	3 (23%)
Mean length (mm)	323	291	317	328	285	313
Perished						
Number	21	2	23 (77%)	6	4	10 (77%)
Mean length (mm)	306	281	304	382	349	380

such as animal tracks and carcass remains adjacent to the transmitters. Fifteen of the transmitters associated with transmitter-implanted fish that died within the Covey Canal system were not recovered; however, we were able to determine these transmitters were not moving, in a lethal location (i.e., dry channel, streambank, or bird nest), or both.

Discussion

Our results indicate that irrigation canals act as sink habitat for fish in the Smiths Fork system. We estimated that 97–214 Bonneville cutthroat trout and 364–412 brown trout were entrained in the Covey Canal system, and that 77% of these entrained trout eventually died when water flows were terminated at the end of the irrigation season. Other studies have also reported entrainment of high numbers of fish in irrigation canals. In the West Gallatin River, Montana, multiple studies have documented fish entrainment, primarily of salmonids, in irrigation canals (Clothier 1953, 1954; Reiland 1997). In 13 canals along the West Gallatin River, Clothier (1953) estimated a loss of 1,989 trout (brown trout, brook trout *Salvelinus fontinalis*, and rainbow trout *O. mykiss*) and 1,022 mountain whitefish during the 1950 and 1951 irrigation seasons combined. Gale (2005) estimated that 8,964 age-0 westslope cutthroat trout *O. clarkii lewisi* were entrained in a single irrigation canal on a tributary of the Bitterroot River in Montana, and these represented 27% of the age-0 cutthroat trout migrating downstream in the river that year. Post et al. (2006) estimated the entrainment of 3,996 rainbow trout, 664 brown trout, and 2,352 mountain whitefish along with 11 other fish species in an irrigation canal diverting water out of the Bow River in Alberta, Canada. We also estimated 195 (95% CI = 0–532) northern leatherside chub (a species of conservation concern) were entrained in the Covey Canal system. Our video observations suggest that northern leatherside chub would have a difficult time returning to the Smiths Fork by swimming upstream through the headgate and thus likely have a high mortality rate once entrained in the canals. The loss of a large number of desert dace *Eremichthys acros* (a species of conservation concern) to irrigation canals in northwestern Nevada in 1989 depressed desert dace numbers through 1996 (Vinyard 1996).

TABLE 2.—Number of attempts and successes of fish attempting to pass upstream through the headgate of the Covey Canal during July 2003. Attempts were determined from 27 h of observations with an underwater video camera.

Taxa	Number of attempts	Number of successes
Bonneville cutthroat trout	29	0
Brown trout	23	0
Mottled sculpin	1	0
Catostomidae	367	2
Cyprinidae	202	0
Total	622	2

Most of the mortality of fish in irrigation canals is due to dewatering at the end of the irrigation season. Irrigation canals thus represent an ephemeral habitat for stream fishes. Use of natural ephemeral habitats by fish is common. For example, many riverine species use seasonally flooded side channels and backwaters for spawning, larval–juvenile rearing, foraging, or to avoid high flow velocities (Junk et al. 1989; Bayley 1991). In most cases, adult fish using these seasonal habitats are able to return to the river main stem when streamflows subside (Kwak 1988; Matheney and Rabeni 1995).

Irrigation canals differ from natural ephemeral habitats such as side channels in two important aspects. First, changes in water flows in the canals are usually instantaneous and can be dramatic, especially at the end of the irrigation season (Beyers and Carlson 1993). Thus, fish entrained in canals do not have time to react to changes in water flow and find escape routes back to main-stem habitats (Clothier 1954). In the Covey Canal, water flows dropped precipitously at the end of the irrigation season in August, going from 0.25 to 0 m^3/s at the headgate within a matter of minutes on August 7, 2003 (Figure 4).

A second way that irrigation canals differ from naturally ephemeral side channels is that the canals typically have a headgate structure to control water flow. Such structures can prevent the return of fish to the river main stem if splash boards create a damlike obstacle to upstream movement. Even when water flows under a sluice gate, upstream return of fish can be inhibited by high flow velocities. This seemed to be the case for the Covey Canal headgate, as 99% (620/622) of the fish that we observed approaching the gate opening were swept back downstream by high flows (Table 2). Although we did not quantify mortality of non-Salmoninae species in the canals, the results from our underwater video monitoring suggest that the irrigation canals are a sink habitat for all species that are entrained.

Carlson and Rahel (2007) reported the potential population-level effects of irrigation canals on brown trout and Bonneville cutthroat trout in the Smiths Fork. They determined population numbers for the entire Smiths Fork basin and the three largest irrigation canals using the sampling design described herein for the irrigation canals and assuming complete loss of entrained fish. Only a small percentage of the basin-wide populations of Bonneville cutthroat trout (1.2–3.3%) and brown trout (0.4–1.2%) were entrained in these canals. We agree with Carlson and Rahel (2007) that these results should be interpreted with caution given that small changes in a population's vital rates can be the difference between population growth and decline (Hilderbrand 2003). Therefore, minimizing the loss of fish in irrigation canals is a management option that should be explored.

Strategies for minimizing the loss of fish in irrigation canals can be considered in terms of the landscape ecology concept of connectivity. Much has been written about the need to maintain connectivity in aquatic systems (Ward and Stanford 1995; Pringle 2003) and how connectivity is important in allowing fish to use spatially disjunct habitats at different seasons or for different life history stages (Fausch et al. 2002). In the case of irrigation canals, fisheries managers are faced with the interesting challenge of maintaining hydrologic connectivity so that water can be delivered without interruption for agricultural needs, while simultaneously preventing biological connectivity, so that fish are not lost into a population sink. Prevention of biological connectivity is usually attempted by putting screens on intake structures or using electrical barriers to deter fish from entering the canals. Screens and electrical barriers are expensive, require ongoing maintenance, and are subject to periodic failure (Clarkson 2004; McMichael et al. 2004; Gale 2005). Thus, these approaches often are only feasible where highly valued native fish or potentially harmful nonnative fish are involved (Zydlewski and Johnson 2002; Stokstad 2003). It may also be possible to minimize fish entrainment by placing headgates in side channels or straight reaches and avoiding river bends where fish moving downstream along the thalweg would be readily drawn into the canal (Bradshaw 1991).

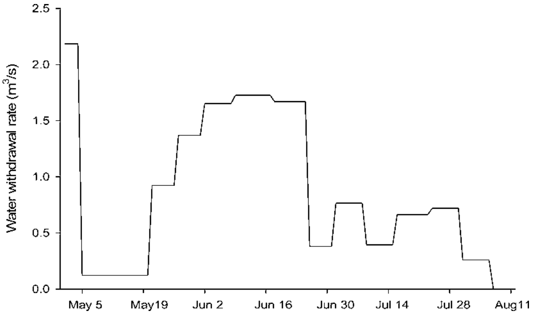

FIGURE 4.—Withdrawals of water from the Smiths Fork via the Covey Canal during the 2003 irrigation season (note the termination of withdrawals on 7 August).

A contrasting strategy is to retain the connectivity between canals and the river, thereby facilitating the movement of fish back to the main stem when water flow declines. Such a strategy requires the design of water intake structures that allow fish to move back through the structure in an upstream direction. This could be done by having water control structures where flow goes under a moveable sluice gate rather than over splash boards so that fish do not have to leap over a structure to return upstream (Bradshaw 1991). However, when a large amount of water is flowing under the sluice gate, high flows impede upstream movement of fish. This appeared to be the case for the Covey Canal headgate. The return of fish to the river main stem may be facilitated by a gradual decline in water flows so that fish have the opportunity to react and move against the canal's flow toward the river main stem. This phenomenon was observed by Clothier (1954) within four canals diverting water from the West Gallatin River in Montana. Unfortunately, changes of water flow into canals are often abrupt because they are dictated by water allocation procedures that give priority to human users, not aquatic biota (Annear et al. 2004). In the absence of gradual flow reductions, few fish appear able to emigrate back to the river main stem by swimming upstream out of an irrigation canal. We found that only 3 out of 43 transmitter-implanted fish showed evidence of emigrating back to the Smiths Fork by swimming upstream through the headgate of Covey Canal. Likewise, Gale (2005) found that only 1 of 74 transmitter-implanted adult westslope cutthroat trout entrained in irrigation canals emigrated back to the Bitterroot River in Montana by swimming upstream through the canals.

A third strategy for dealing with fish entrainment ignores the issue of biological connectivity and relies on rescuing fish stranded in canals by means of seines, electrofishing, or nets (Good 1990). Such efforts may generate much good will with the public but are expensive and arduous to carry out and are only effective if stranded fish are concentrated in a few areas of the canal system (Good 1990; Post et al. 2006). As with screening, rescue operations are usually reserved for a few fish species of sport or conservation value.

The movement and the ability to escape of trout entrained in the Covey Canal system were influenced by the presence of natural stream crossings and siphons. While natural stream crossings were shown to aid in the return of entrained trout to the Smiths Fork (i.e., Brunner Creek), siphons are a complicating factor for fish entrained in the Covey Canal system. Siphons are used to transport irrigation flows across valleys and rely on a difference in elevation and the resultant hydraulic head to keep water moving down one side of the siphon and up the other side. Inside the siphon, water is completely enclosed in a pipe and is moving at high velocities. This makes it unlikely that fish that have passed through a siphon will reenter the siphon and successfully swim upstream to the other end (for hundreds of meters, in some cases) through high water velocities in total darkness. During our study we found that two transmitter-implanted trout passed downstream through siphons, we also released two transmitter-implanted trout downstream of siphons. However, none of the four transmitter-implanted trout that were located downstream of a siphon moved upstream through these structures. Siphons thus appear to function as one-way valves in terms of fish movement through an irrigation system, allowing fish to move downstream but not upstream. Schmetterling (2003) found that a dam on a Montana river also functioned as a one-way valve for trout in the system. Fish that passed over the dam entered a sink habitat and were lost from the spawning population unless rescued and moved back upstream.

The spatial patterns in the distribution of fish within the Covey Canal system indicate the importance of developing strata and identifying areas of fish concentration throughout a system when trying to obtain a population estimate of entrained fish. Headgate structures, natural stream crossings, and siphons created areas where fish tended to congregate, especially as flows declined. If we had only used random site selection, some of the congregated sites would undoubtedly have not been sampled, resulting in an underestimate of the entrained population size. Conversely, if population estimates from congregated sites were then extrapolated to the rest of the canal section, the population size would have been overestimated. These possible pitfalls stress the importance of a priori knowledge of the system when determining a sample design for obtaining a population estimate of irrigation canals using electrofishing.

Understanding how human activities can create sink habitats is important if we are to manage streams from a landscape perspective (Fausch et al. 2002). In the absence of screens or electrical barriers, irrigation canals function as sink habitats for stream fishes. Irrigation canals thus represent a situation where fisheries managers need to reduce rather than enhance connectivity in stream systems (Rahel 2007). Screens and electrical barriers are effective but are expensive and require continual maintenance. Their use is likely to be constrained to situations involving important game fish or species of conservation concern. For the many other situations where water is diverted into irrigation canals, there is a need for more research into how location of headgates along the stream corridor, upstream passage through headgates, and management of flow reductions can be used to minimize initial entrainment and maximize eventual return of entrained fish.

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References

Adams, N. S., D. W. Rondorf, S. D. Evans, and J. E. Kelly. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of juvenile Chinook salmon. Transactions of the American Fisheries Society 127:128–136.

Annear, T., I. Chisholm, H. Beecher, A. Locke, P. Aarrestad, C. Coomer, C. Estes, J. Hunt, R. Jacobson, G. Jobsis, J. Kauffman, J. Marshall, K. Mayes, G. Smith, C. Stalnaker, and R. Wentworth. 2004. Instream flows for riverine resource stewardship, revised edition. Instream Flow Council, Cheyenne, Wyoming.

Bayley, P. B. 1991. The flood pulse advantage and the restoration of river–floodplain systems. Regulated Rivers: Research and Management 6:75–86.

Beamesderfer, R. C. P., D. L. Ward, and A. A. Nigro. 1996. Evaluation of the biological basis for a predator control program on northern squawfish (*Ptychocheilus oregonensis*) in the Columbia and Snake rivers. Canadian Journal of Fisheries and Aquatic Sciences 53:2898–2908.

Beyers, D. W., and C. A. Carlson. 1993. Movement and habitat use of triploid grass carp in a Colorado irrigation canal. North American Journal of Fisheries Management 13:141–150.

Bradshaw, W. H. 1991. Discussion on the magnitude, circumstances, and means of reducing fish losses resulting from off-stream diversions. Wyoming Game and Fish Department, Cheyenne.

Brown, R. B., and W. C. Mackay. 1995. Fall and winter movements of and habitat use by cutthroat trout in the Ram River, Alberta. Transactions of the American Fisheries Society 124:873–885.

Bunnell, D. B., J. J. Isely, K. H. Burrell, and D. H. Van Lear. 1998. Diel movement of brown trout in a southern Appalachian river. Transactions of the American Fisheries Society 127:630–636.

Carlson, A. C., and F. J. Rahel. 2007. A basinwide perspective on entrainment of fish in irrigation canals. Transactions of the American Fisheries Society 136:1335–1343.

Clarkson, R. W. 2004. Effectiveness of fish barriers associated with the central Arizona project. North American Journal of Fisheries Management 24:94–105.

Clothier, W. D. 1953. Fish loss and movement in irrigation diversions from the West Gallatin River. Montana Journal of Wildlife Management 17:144–158.

Clothier, W. D. 1954. Effect of water reductions on fish movement in irrigation diversions. Journal of Wildlife Management 18:150–160.

Colyer, W. T., J. L. Kershner, and R. H. Hilderbrand. 2005. Movements of fluvial Bonneville cutthroat trout in the Thomas Fork of the Bear River, Idaho–Wyoming. North American Journal of Fisheries Management 25:954–963.

Dunning, J. B., B. J. Danielson, and H. R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65:169–175.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483–498.

Furniss, M. J., T. D. Roelofs, and C. S. Yee. 1991. Road construction and maintenance. Pages 297–323 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Gale, S. B. 2005. Entrainment losses of westslope cutthroat trout into screened and unscreened irrigation canals on Skalkaho Creek, Montana. Master's thesis. Montana State University, Bozeman.

Good, W. R. 1990. A fyke net for rescue of fish stranded in culverts. North American Journal of Fisheries Management 10:115–117.

Hilderbrand, R. H. 2003. The roles of carrying capacity, immigration, and population synchrony on persistence of stream-resident cutthroat trout. Biological Conservation 110:257–266.

Jakober, J. J., T. E. McMahon, R. F. Thurow, and C. G. Clancy. 1998. Role of stream ice on fall and winter movements and habitat use by bull trout and cutthroat trout in Montana headwater streams. Transactions of the American Fisheries Society 127:223–235.

Johnson, J. B., T. E. Dowling, and M. C. Belk. 2004. Neglected taxonomy of rare desert fishes: congruent evidence for two species of leatherside chub. Systematic Biology 53:841–855.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river–floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106:110–127.

Keinath, D. B., B. Heidel, and G. P. Beauvais. 2003. Wyoming plant and animal species of concern. University of Wyoming, Laramie.

King, A. J., and J. P. O'Connor. 2007. Native fish entrapment in irrigation systems: a step towards understanding the significance of the problem. Ecological Management and Restoration 8:32–37.

Kwak, T. J. 1988. Lateral movement and use of floodplain habitat by fishes of the Kankakee River, Illinois. American Midland Naturalist 120:241–249.

Leslie, J. K., C. A. Timmins, and C. A. T. Burlington. 1990. The community of young fish in drainage ditches in southwestern Ontario. Archiv für Hydrobiologie 118:227–240.

Matheney, M. P., IV, and C. F. Rabeni. 1995. Patterns of movement and habitat use by northern hog suckers in an Ozark stream. Transactions of the American Fisheries Society 124:886–897.

McMichael, G. A., J. A. Vucelick, C. S. Abernethy, and D. A. Neitzel. 2004. Comparing fish screen performance to physical design criteria. Fisheries 29(7):10–16.

Post, J. R., B. T. van Porten, T. Rhodes, P. Askey, and A. Paul. 2006. Fish entrainment into irrigation canals: an analytical approach and application to the Bow River, Alberta, Canada. North American Journal of Fisheries Management 26:875–887.

Pringle, C. M. 2003. What is hydrologic connectivity and why is it ecologically important? Hydrological Processes 17:2685–2689.

Pulliam, H. R. 1988. Sources, sinks, and population regulation. American Naturalist 132:652–661.

Rahel, F. J. 2007. Biogeographic barriers, connectivity, and biotic homogenization: it's a small world after all. Freshwater Biology 52:696–710.

Raymond, H. L. 1979. Effects of dams and impoundments on migrations of juvenile Chinook salmon and steelhead from the Snake River, 1966 to 1975. Transactions of the American Fisheries Society 108:505–529.

Reiland, E. W. 1997. Fish loss to irrigation canals and methods to reduce these losses on the West Gallatin River, Montana. Master's thesis. Montana State University, Bozeman.

Roberts, J. J., and F. J. Rahel. 2005. Accuracy of aerial telemetry in fisheries studies. North American Journal of Fisheries Management 25:660–666.

Schlosser, I. J., and P. L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Pages 392–401 *in* J. L. Nielsen, editor. Evolution and the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society, Symposium 17, Bethesda, Maryland.

Schmetterling, D. A. 2003. Reconnecting a fragmented river: movements of westslope cutthroat trout and bull trout after transport upstream of Milltown Dam, Montana. North American Journal of Fisheries Management 23:721–731.

Schrank, A. J., and F. J. Rahel. 2004. Movement patterns of inland cutthroat trout (*Oncorhynchus clarkii utah*): management and conservation implications. Canadian Journal of Fisheries and Aquatic Sciences 61:1528–1537.

Stokstad, E. 2003. Can well-timed jolts keep out unwanted exotic fish? Science 301:157–158.

U.S. Fish and Wildlife Service. 2001. 12-month finding for a petition to list the Bonneville cutthroat trout as threatened throughout its range. Federal Register 66:195(9 October 2001):51362–51366.

Van Deventer, J. S., and W. S. Platts. 1985. A computer software system for entering, managing, and analyzing fish capture data from streams. U.S. Forest Service Research Note INT-352.

Vinyard, G. L. 1996. Distribution of a thermal endemic minnow, the desert dace (*Eremichthys acros*), and observations of impacts of water diversion on its population. Great Basin Naturalist 56:360–368.

Ward, J. V., and J. A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research and Management 11:105–119.

Zar, J. H. 1984. Biostatistical analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

Zydlewski, G. B., and J. R. Johnson. 2002. Response of bull trout fry to four types of water diversion screens. North American Journal of Fisheries Management 22:1276–1282.