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[Article]

Fish Entrainment into Irrigation Canals: an Analytical Approach and Application to the Bow River, Alberta, Canada

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Abstract.—The Carseland Canal on the Bow River, Alberta, diverted water at a rate of 1.4–37.7 m^3/s during the 2003 irrigation season. We estimated daily entrainment rates of rainbow trout *Oncorhynchus mykiss*, brown trout *Salmo trutta*, and mountain whitefish *Prosopium williamsoni* throughout the diversion season using population assessments of fish in the Bow River and the irrigation canal coupled to an estimate of the evacuation rate of intentionally entrained fish. Total entrainment during the irrigation season was estimated at 3,996 rainbow trout, 664 brown trout, and 2,352 mountain whitefish. Large fish (>150 mm fork length [FL]) made up 42.0% of the total number of entrained rainbow trout, 17.0% of entrained brown trout, and 0.5% of entrained mountain whitefish, representing 1.1, 0.8, and 0.3% of the total mortality observed in these Bow River populations. Earlier estimates of canal losses based on fall rescues of fish suggest that entrainment varies annually and that the 2003 estimates were low for rainbow trout and brown trout and high for mountain whitefish. We also identified 11 additional species that were either entrained or resident in the system within the canal and associated settling pond.

Large numbers of recreational and other fish species are lost annually to water diversions from rivers, lakes, and estuaries. Impingement or entrainment has been documented at irrigation canals, intakes for power plants and hydroelectric facilities, and intakes for domestic or industrial use (Clothier 1953, 1954; Stober et al. 1983; Stevens et al. 1985; Tomljanovich and Heuer 1986; Moyle et al. 1992; Spindler 1955; Carter and Reader 2000; Hadderingh and Jager 2002). Many more studies of impingement and entrainment are only presented in the unpublished literature (see reviews in Reiland 1997; Earle and Post 2001; van Poorten and Post 2004). The approaches, methodologies, and rigor of quantitative conclusions from these diverse studies are highly variable. From the standpoint of anglers, any fish loss is unacceptable because it is perceived as reducing recreational opportunities. From the perspective of water managers, the loss of some fish is an acceptable cost given the substantial economic benefit of agricultural production, energy generation, industrial economies, and domestic needs. The key concern for fishery managers is the impact of fish loss from the donating water body at the population and community levels.

Competition for water is particularly acute in the dry interior of North America, where demand for water to irrigate crops is high and increasing. Water extraction for irrigation in spring-freshet-driven rivers of the western cordillera has led to extraction regulations based largely on instream flow needs (Bovee 1982) for fish during base flow conditions present after the freshet. Less attention has been placed on the impacts of fish loss than on water loss from rivers. The obvious solution to fish loss into diversion canals is the use of screening and other technological barriers (Nestler et al. 1992; Reiland 1997; Zydlewski and Johnson 2002; Clarkson 2004). At the scale of large diversions, these barriers are costly, require extensive maintenance, and may reduce water extraction efficiency. Therefore, their installation should be based on an assessment of the gains in target fish populations relative to the costs of barrier construction and maintenance; however, this type of quantitative biological information on which to make rational decisions is often lacking.

The goal of this study was to develop and apply a general analytical approach to assess the timing, magnitude, and population-level impact of fish entrainment into irrigation canals from donor populations. Our fourfold approach was to (1) quantify the seasonal

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pattern in entrainment rates; (2) integrate these rates across the water diversion season to estimate total annual entrainment; (3) estimate the proportion of total mortality of the donor population that is explained by canal-induced mortality; and (4) examine correlates of entrainment rate. These approaches were applied to three sport fish species: rainbow trout *Oncorhynchus mykiss*, brown trout *Salmo trutta*, and mountain whitefish *Prosopium williamsoni*, which currently provide a "blue-ribbon" sport fishery. The specific application focused on a large irrigation canal that extracts water from the Bow River in southern Alberta, Canada.

Methods

Study Site

Bow River.—The Bow River is a major glacial-fed tributary of the South Saskatchewan River basin originating in the Rocky Mountains of southern Alberta and flowing eastward (Figure 1). The river near Calgary attains a much higher productivity from nutrient inputs contributed by municipal wastewater (Sosiak 2002). This fertilization is responsible for supporting productive rainbow trout, brown trout, and mountain whitefish sport fisheries downstream of Calgary (Sosiak 2002; Rhodes 2005).

Carseland Bow River Headworks Canal.—The Carseland Bow River Headworks Canal (hereafter, Carseland Canal) flows from the headworks on the Bow River (southeast of Carseland, Alberta) into McGregor Reservoir, 66 km downstream (Figure 1). The headworks are situated on the south bank of the Bow River immediately upstream from the Carseland weir. The water diversion period for the canal typically extends from mid-April to mid-October (van Poorten and Post 2004). In 2003, water was diverted from the Bow River through the Carseland Canal from April 7 to October 10. Discharge throughout the 2003 diversion period ranged between 1.4 and 37.7 m^3/s (Figure 2). The Carseland Canal represents a substantial extraction from the Bow River; during August, discharge into the canal exceeds discharge in the river (Figure 2). The headworks were closed partially or totally to clear debris out of the structure 1–4 times/d between May 1 and October 8, 2003.

Most of the upstream 10 km are armored with rock on both sides of the canal and generally have a constant bank slope with a flat bottom. The bed is about 13 m wide and 3.4 m deep when the canal is at full operating capacity (van Poorten and Post 2004). Very few velocity breaks are available throughout this section of canal. Slower water is found in a small number of areas associated with bends, areas with nonarmored banks, bridge abutments, and three side channels.

At the end of the diversion period, the headworks are closed to prevent ice damage to the water control structures throughout the canal. Flows are reduced over about 5 d. After closure, complete dewatering of the canal takes about 2 weeks, after which water is restricted to a few low-lying areas including the settling pond below kilometer 10 (Figure 1). Previous unsubstantiated reports assumed that the water in these areas froze to the bottom during the winter (RL&L Environmental Services, Ltd. 2000); however, anecdotal evidence from local residents disputes this, suggesting that water can be drawn from the settling pond year-round and that overwintering of fish is possible (van Poorten and Post 2004).

Model Development and Parameter Estimation

We developed models and estimated parameters to determine the entrainment rate of fish into the Carseland Canal, impacts of this loss to the donor Bow River populations, and interannual variation in this loss (see Table 1 for model parameters, units, and estimates).

Analytical approach to estimating entrainment rate.—Our approach to estimating total entrainment of Bow River fish into the Carseland Canal was analogous to that developed by Elliot and Persson (1978) to estimate food consumption rate by fish. If the number of fish in a canal is N, then the rate of change in N (dN/dt) can be written as

$$\frac{dN}{dt} = E - RN \tag{1}$$

where E is the entrainment rate and R is the per capita evacuation rate of fish from the upper 10 km of the canal. The design of the canal headworks prevents the escape of fish from the canal back into the Bow River. Therefore, fish are only lost from the system by the evacuation rate, representing fish that are flushed downstream into the settling pond and lower reaches of the canal or McGregor Reservoir (Figure 1). This is a reasonable assumption provided that R is larger and operates over a shorter period (i.e., days) relative to other sources of mortality. The number of fish present in the canal at time t can be solved as

$$N_t = \frac{E}{R}(1 - e^{-Rt}) + e^{-Rt}N_0, \tag{2}$$

where N_0 is the number of fish present in the canal at time 0. Under the assumption that E and R remain constant, the total entrainment of fish (L) is simply calculated as Et; we can solve L from the observed number of fish in the canal at two times (j and $j-1$) as

$$L = \frac{(N_j - N_{j-1} \cdot e^{-Rtj})Rt_j}{1 - e^{-Rtj}}, \tag{3}$$

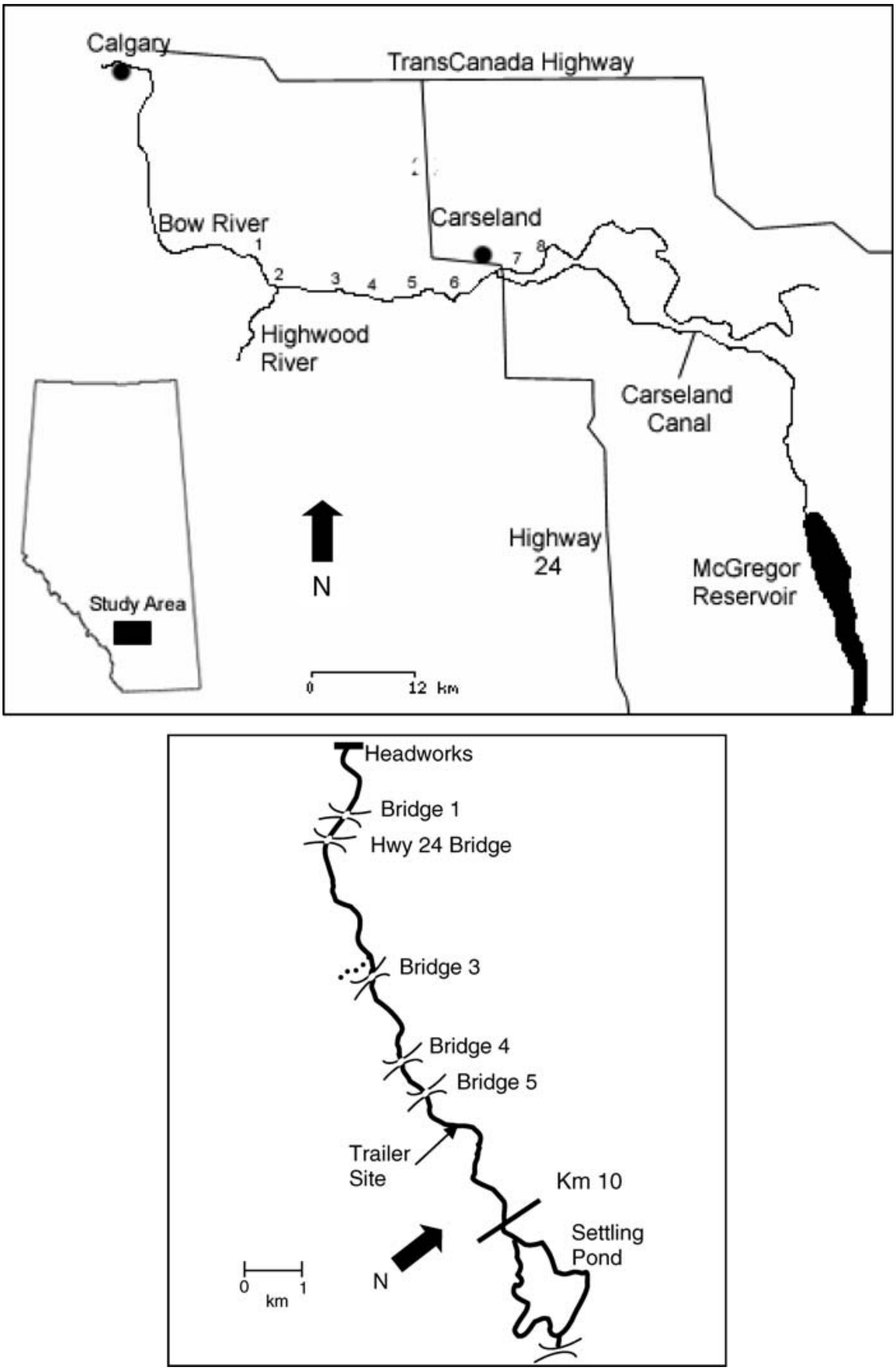

FIGURE 1.—Map of the study area in Alberta, Canada, including the Bow River and Carseland Canal (top panel; inset shows location within Alberta). The Bow River flows south to east from Calgary, and the Carseland Canal flows south from the headworks, situated near Carseland. Bow River sample sites located upstream (1–6) and downstream (7–8) of the headworks are indicated. The bottom panel shows the upper 10 km of the canal from the headworks to the settling pond (km 11).

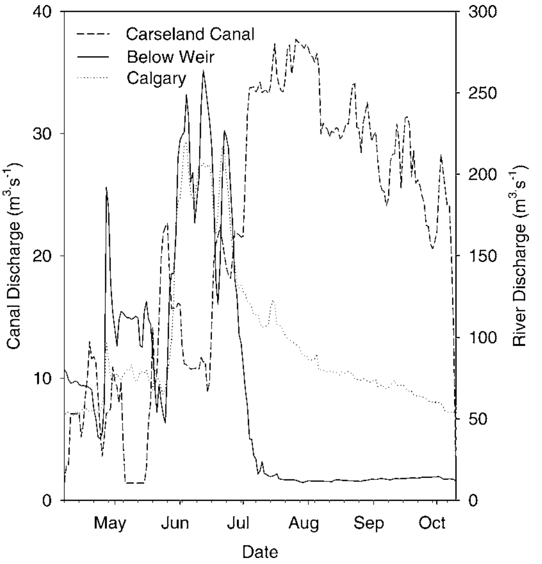

FIGURE 2.—Mean daily discharge during the 2003 irrigation season in the Carseland Canal, Alberta (measured at the headworks); the Bow River at Calgary, Alberta (upstream of the weir); and the Bow River downstream of the weir. Bow River discharge data are available from Environment Canada (2005).

where t is the time (d) between j and $j - 1$, and R-values are measured independently.

We expected both E and R to vary with time. However, because the upper 10 km of canal are relatively uniform and contain little habitat for fish to maintain position, we expected R to vary much less than the entrainment rate E, especially given that discharge in the canal is uniform from July until the end of the irrigation season. On the other hand, we had little reason to expect E to remain constant across the irrigation season; in fact, we expected E to vary substantially throughout the season as fish in the Bow River move past the headworks. When we divided the irrigation season into discrete short periods of several days, it was reasonable to model E as a constant value over this time. Therefore, the total entrainment rate L was estimated as the sum of these discrete intervals:

$$L = \sum_{j=1}^{k} \frac{(\hat{N}_j - \hat{N}_{j-1} \cdot e^{-Rt_j})Rt_j}{1 - e^{-Rt_j}}, \tag{4}$$

where L is the annual entrainment in numbers of fish; t_j is the time (d) between abundance estimates; k is the number of abundance estimates; $\hat{N}_j$ is the abundance estimate in the upper 10 km of the canal at j; $\hat{N}_{j-1}$ is the abundance estimate in the previous time period; and R is assumed to be constant over all time periods.

Estimates of abundance by species for a series of discrete time intervals (i.e., N_j) were calculated as the product of catch per unit effort (CPUE) and a catchability estimate (q; proportion of population caught per unit effort). Entrainment was estimated for the target species for 12 intervals ($k = 12$ abundance estimates) from canal opening ($j = 0$) to closing ($j = 12$); it was assumed that N_0 was equal to 0 at canal opening. The duration of these intervals was typically 10 d but varied somewhat depending on timing of field sampling in the Bow River (see below).

Fish in the canal were sampled throughout the diversion period from May 28 to October 9, 2003. Fish were captured in the upper 10 km of the canal by use of gill nets (959 gill-net panel-nights), each set for about 24 h. Nets were set continuously throughout the sampling season in gangs of two to seven panels. Gill-net panels had a stretched-mesh size of 2.54, 3.18, 3.81, 5.08, 6.35, 7.62, or 8.89 cm, and each panel constituted one unit of effort (1 net-night). Gill nets were set along the canal at a 10–20° angle to the shoreline or randomly within the settling pond. Gill nets were generally set in slower water; bends in the canal or near the entrance of side channels. Target species were measured for fork length and weight and were checked for any tags attached during Bow River electrofishing (see Population Assessment). Released target species also received clips in the lower caudal fin for later identification. All other fish species were identified and counted. This sampling yielded a mean daily CPUE for each time interval by target species (C_s/E; CPUE for species s).

We estimated catchability by intentionally entraining a known number of marked fish. Intentional entrainment of fish in the canal was performed during July 23–25, September 3–5, and October 7–9. The entrainment experiments were conducted on white suckers *Catostomus commersonii* because sufficient numbers of the target species were unavailable. White suckers were captured in fyke nets in the settling pond, measured for fork length, and given a clip on either the right or left pelvic fin (depending on marking period). Fish were then put in cool, aerated water, transported to the canal headworks, and released back into the canal. In July and September, fish were recaptured using gill and fyke nets in the canal and settling pond in the days after release. All recaptured fish were examined for fin clips and measured for fork length. Fish released in October were recaptured during the "fish rescue" (see below).

Catchability of fish by gill nets (q) was estimated as the proportion of white suckers entrained intentionally in July and September that were later recaptured, adjusted for both gill-net effort and R. We assumed a linear relation between catch and gill-net effort (i.e.,

TABLE 1.—Parameter set for a model designed to estimate the number of Bow River rainbow trout, brown trout, and mountain whitefish entrained in the Carseland Canal, Alberta.

Parameter	Description	Units	Estimate (95% CI)
R	Per capita evacuation rate	Fish $\cdot$ fish^{-1} $\cdot$ d^{-1} (%)	11.0 (10.1–12.0)
L_{rntr}	Total entrainment of rainbow trout in current year	Number of fish	3,996 (2,113–8,696)
L_{bntr}	Total entrainment of brown trout in current year	Number of fish	664 (356–1,448)
L_{mnwh}	Total entrainment of mountain whitefish in current year	Number of fish	93,850 (49,748–20,2991)
e_{rntr}	Relative efficiency of gill nets in capturing rainbow trout versus white suckers	Ratio	1.12
e_{bntr}	Relative efficiency of gill nets in capturing brown trout versus white suckers	Ratio	9.79
e_{mnwh}	Relative efficiency of gill nets in capturing mountain whitefish versus white suckers	Ratio	1.05
$\hat{N}_{s,j}$	Estimated abundance of species s at period j in the upper 10 km of the canal	Number of fish	Dynamic
q_{whsc}	Catchability of white suckers for one unit of gill-net effort	Fish·fish^{-1} $\cdot$ gill-net-night^{-1}	1.41×10^{-4} (0.74×10^{-4} to 2.47×10^{-4})
$\hat{N}_{\text{canal}}$	Number of marked white suckers during October 7–9 estimated to be present in the upper 10 km of the canal after October 10	Number of fish	379
$\hat{N}_{\text{sp}}$	Number of white suckers marked during October 7–9 estimated to be in the settling pond after October 10	Number of fish	388
q_{fyke}	Catchability of fyke nets	Fish·fish^{-1} $\cdot$ fyke-net-night^{-1}	1.29×10^{-3}
e_{rescue}	Efficiency of fish rescue in canal	Ratio (%)	41.4 (30.3–59.4)
x	Canal length swept during fish rescue	Kilometers	7
$\hat{N}_{t+x}$	Number of marked white suckers entrained intentionally on September 3–5 and estimated to be present during the fish rescue	Number of fish	30 (21–40)

constant catchability). Since fish are lost in the upper 10 km of canal through evacuation, the number of entrained white suckers present and available for capture decreases with time. The number of suckers available for capture was estimated by applying R to the number of fish entrained on each day:

$$M_t = \sum_{i=1}^{n} M_i \cdot \exp^{-R(t-t_i)}, \tag{5}$$

where M_t is the number of marked fish remaining on recapture day t; M_i is the number of fish that were marked on day t_i ($t \geq t_i$); n is the number of entrainment events before t; and t_i and t are expressed in days from the start of canal operation. Therefore, the number of marked white suckers remaining in the canal after an entrainment event decreases exponentially until newly marked white suckers are entrained at time t_i.

The maximum likelihood estimate for gill-net catchability was calculated independently on each recapture day assuming a binomial distribution of catch (corrected for gill-net effort) for both the July and September experiments. The overall catchability of gill nets and confidence limits from the likelihood profiles were calculated from the joint likelihood of all recapture days. Since we needed catchability estimates for the three target species, we estimated their catchability relative to white suckers by use of catch rates from the fish rescue (see below). Relative efficiency (e_s) for target species s was calculated as

$$e_s = \frac{\left(C_s / C_{\text{s,rescue}}\right)}{\left(C_{\text{whsc}} / C_{\text{whsc,rescue}}\right)}, \tag{6}$$

where C_s is the catch of a target species in the final 14 d of regular canal sampling with gill nets and $C_{s,\text{rescue}}$ is the catch of a target species in the fish rescue. The variables C_{whsc} and $C_{\text{whsc,rescue}}$ are as above but represent white suckers. All catch parameters are in numbers of fish, and efficiency is unitless. This efficiency estimate allows the catchability for white suckers to be corrected for potential differences in habitat use and behavior between white suckers and the target species.

Abundance for each target species during each sampling period j can now be estimated as

$$\hat{N}_{s,j} = \frac{C_{s,j}}{E \cdot q_{\text{whsc}} \cdot e_s}, \tag{7}$$

where $\hat{N}_{s,j}$ is the estimated abundance of target species s at period j, $C_{s,j}$ is the catch of target species s at period j, E is effort (gill-net panel-nights), q_{whsc} is the catchability of white suckers, and e_s is the efficiency coefficient for species s. Confidence limits on $\hat{N}_s$ were calculated using the upper and lower confidence limits for q_{whsc}. The assumption inherent in this technique is that the uncertainty in catchability is of the same magnitude in the target species as in white suckers and that the relative differences are best approximated by e_s. This error propagation technique was used throughout the study to estimate uncertainty in entrainment rates of the target species.

The evacuation rate of fish through the canal (R) was estimated from the decline in the number of white suckers entrained intentionally at the headworks at time t (N_t) to some later time (N_{t+x}). The evacuation rate model is:

$$\hat{N}_{t+x} = N_t \cdot e^{(-R \cdot x)}, \tag{8}$$

where N_{t+x} is the estimated number of entrained white suckers that remained in the canal x days later, N_t is the number of white suckers entrained, and x is time (d). We could not use the gill-net catch data to estimate R, as our estimate of catchability from the gill nets depended on R (i.e., data were not unique). However, fish captured during the fish rescue provided an independent estimate of abundance (see below). The intentional entrainment of 1,370 marked white suckers on September 3–5 (N_t) and the estimated number of these fish present during the rescue ($\hat{N}_{t+x}$) were used to estimate R. The value $\hat{N}_{t+x}$ was estimated by dividing the number of marked fish recaptured during the rescue by the efficiency of the fish rescue (see Interannual Variability). In addition to R, we also calculated the number of days required for half of the entrained fish to evacuate from the upper 10 km of the canal as $t_{0.5} = [-\log_e(0.5)]/R$.

Size selectivity of entrainment was assessed by contrasting size-frequency distributions of target species captured in the canal and settling pond in gill nets and fyke nets with size-frequency distributions of fish caught in the Bow River (see next section).

We used a second approach to independently estimate canal entrainment of the target species through a mark–recapture experiment. Rainbow trout, brown trout, and mountain whitefish were sampled from the Bow River using two boat-mounted electrofishers over three time periods in 2003: spring (May 20–23 and 26–27), summer (July 8–11), and fall (September 22–24) at eight 2-km-long sections along the river (Figure 1). Because of low water levels, locations 1 and 2 were not sampled in September. Captured fish were measured for fork length (nearest mm), total length (nearest mm), and mass (nearest g). Fish larger than or equal to 150 mm were tagged with a Floy FD-94 tag inserted just below the dorsal fin. Fish smaller than 150 mm were adipose fin clipped, and a decimal coded wire tag (Northwest Marine Technology, Shaw Island, Washington) was injected into the rostrum of each fish. This procedure allowed for individual identification of all recaptured fish. Fish were held in large, cotton-mesh dip nets or in a cotton-mesh holding pen in flowing water until they recovered sufficiently and then were released within 1 km of the point of capture. All fish captured in the canal and settling pond were examined for these tags.

To estimate the number of river-marked fish resident in the canal, a discrete model was developed. The number of marked fish present in the river at any time (M_{Bt}) is

$$M_{B_t} = M_{B_{t-1}} \cdot e^{-(\delta_c + \delta_o) \cdot \Delta t}, \tag{9}$$

where M_{Bt-1} is the number of river-marked fish in the river at time $t - 1$, Δt is the time between t and $t - 1$ (d), δ_c is the daily canal-induced mortality rate (m_c/365) and δ_o is the daily mortality due to all other sources. Since fish were marked in the river during three periods, each period added newly marked fish to the river. Therefore, the number of fish marked in the Bow River that are present in the canal at any time (M_{Ct}) is

$$M_{C_t} = M_{B_{t-1}} \cdot (1 - e^{-\delta_c \Delta t}) + M_{C_{t-1}} \cdot e^{-R\Delta t}, \tag{10}$$

This model can be used to predict the number of marked fish present in the canal at any time and, therefore, the probability of capturing a marked fish in the canal.

Population-level impacts.—We assessed the impact of canal-induced mortality on Bow River fish populations by partitioning total mortality in the donor population into canal and noncanal components. Total mortality (m_T) was calculated by use of a catch curve for each target species (Haddon 2001) based on data from a population assessment completed in 2001 for the entire 169 km coldwater portion of the Bow River sport fishery (T.R. and P.A., unpublished data). Scales for a subsample of fish from each target species were used for aging. A length–age key was generated based on aged fish and was applied to the length-frequency distribution for all fish. Total instantaneous annual mortality was estimated from the decline in the natural log of abundance by age for age-classes that were fully recruited into the sampling gear. The annual instantaneous rate of canal-induced mortality (m_c) was calculated over an annual time step:

$$m_c = \frac{\log_e\left(\frac{N_{B_0} - L}{N_{B_0}}\right)}{y}, \tag{11}$$

where L is total entrainment for fish 150 mm or greater, N_{B_0} is the total abundance of the population in the river, and y is time (years). Instantaneous annual mortality from all other sources (m_o) is calculated as

$$m_o = m_T - m_c. \tag{12}$$

Total abundance of Bow River populations (N_{B_0}) was determined from the 2001 population assessment (T.R. and P.A., unpublished data). These population assessments focused only on 150-mm and larger fish; therefore, our canal entrainment estimates were recalculated for fish of this size for comparison with the previous data.

Interannual variability.—Fish rescues have taken place on the Carseland Canal annually from 1998 to 2003 after closure of the canal headworks in the fall (RL&L Environmental Services, Ltd. 2000; Eisler and Brewin 2002; Eisler et al. 2003; van Poorten and Post 2004). The intention of the fish rescue is to return fish to the Bow River that would otherwise perish as canal waters recede. Fish were removed from the canal by means of two methods. The first (carried out between 1998 and 2000) involved installing a portable dam at kilometer 7 (Figure 1) to maintain water between the dam and the headworks. Fish were subsequently captured by means of backpack electrofishing that started at the headworks and proceeded downstream. To prevent fish from escaping, a blocking net was placed immediately behind the electrofishers. When the blocking net was within about 10 m of the portable dam, multiple-pass electrofishing was used to remove fish from the small enclosure. This was repeated two or more times over about a 2-week period. The second method for removing fish from the canal (2001–2003) involved installing a blocking net at kilometer 2 and electrofishing downstream from the headworks, again with a blocking net moving downstream behind the electrofishers to prevent escape. This was performed only once and was usually completed over 2 d. The 2003 fish rescue was enhanced to maximize the return of river-marked and intentionally entrained fish. Fish were also captured between two blocking nets set at 5 and 10 km downstream from the headworks to increase the sample size of captured fish. All captured fish were sorted into species, measured, weighed, and examined for fin clips and Floy tags. Fish were subsequently returned to the Bow River upstream from the canal headworks.

Efficiency of the 2003 fish rescue was estimated as the proportion of the fish present in the upper 10 km of the canal that were rescued. During the rescue in 2003, fish could not move past the settling pond because of an earthen dam built on October 10 downstream from the settling pond (kilometer 11). A known number of white suckers was marked and intentionally entrained on October 7–9 just before the closure of the headworks and installation of the dam on October 10. We then estimated abundance of marked white suckers in the upper 10 km of the canal by subtracting the estimated number of marked fish residing in the settling pond (i.e., fish evacuated from the upper 10 km) from all marked fish released on October 7–9.

An estimate of the number of fish in the settling pond was made based on the CPUE of white suckers in fyke nets and an independent estimate of catchability for the fyke nets. Fyke-net catchability was estimated from data on a closed population of rainbow trout captured in nets similar in mesh size and dimensions to those of the canal (van Poorten 2003). Likelihood-profile confidence limits for fyke-net catchability assumed a binomial distribution of recaptures.

Given these data, the number of marked white suckers present in the upper 10 km of the canal after October 10 was estimated as

$$\hat{N}_{\text{canal}} = \hat{N}_{\text{marked}} - \left(\frac{\hat{N}_{sp}}{q_{\text{fyke}} \cdot E}\right), \qquad (13)$$

where $\hat{N}_{marked}$ is the number of fish marked during the October 7–9 intentional entrainment, $\hat{N}_{sp}$ is the number of marked fish recaptured in the fyke nets set in the settling pond during the fish rescue, q_{fyke} is the catchability of fyke nets with confidence limits (from above), and E is the fyke net effort (fyke-net-nights) during the fish rescue.

The efficiency of the fish rescue was estimated as

$$e_{\text{rescue}} = \frac{\left(\frac{n_{\text{rescue}}}{\hat{N}_{\text{canal}}}\right)}{\left(\frac{x}{T}\right)}, \qquad (14)$$

where n_{rescue} is the number of fish marked and intentionally entrained during October 7–9 that were rescued, N_{canal} is the estimated number of marked fish in the upper 10 km of the canal, x is the number of kilometers swept during the rescue out of the total kilometers T ($x = 7$). Dividing by the proportion of area considered allowed for the fish rescue efficiency to be applied to the entire upper 10 km of the canal.

To determine interannual variability of entrainment, it is necessary to examine past fish rescues in the Carseland Canal. An estimate of entrainment in past years was made using the following formula:

$$L_{s,y} = \frac{L_s \cdot C_{s,\text{rescue},y}}{C_{s,\text{rescue}}}, \qquad (15)$$

where $L_{s,y}$ is the estimated entrainment for one of the target species (s) in a past year (y), L_s is the entrainment in the current year, $C_{s,\text{rescue},y}$ is the catch of the target species in the fish rescue in a past year, and $C_{s,\text{rescue}}$ is the catch of the target species in the 2003 fish rescue. All parameters are in numbers of fish. We applied this equation to the fish rescue results for 2001 and 2002, because methods were similar to those in the 2003 fish rescue. Methods used in the fish

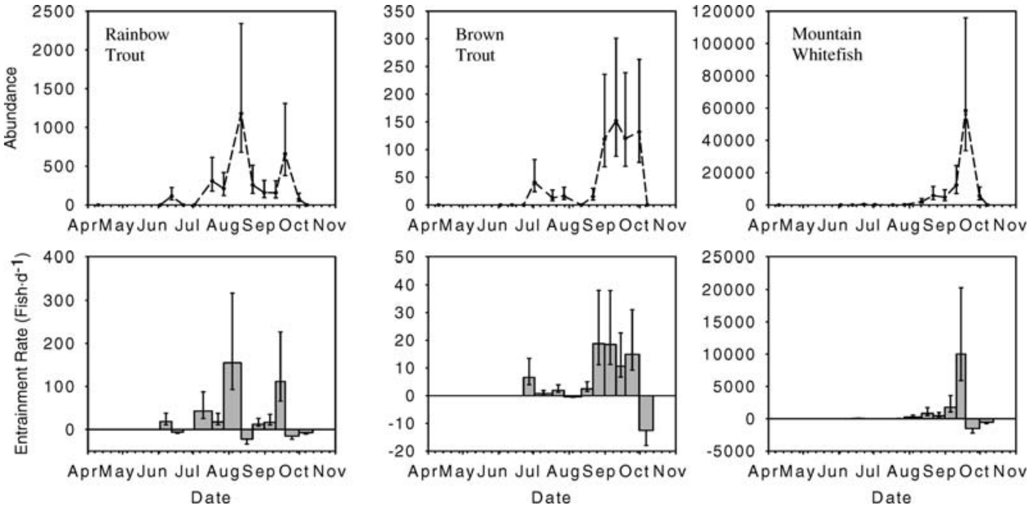

FIGURE 3.—Seasonal abundance (with 95% CI; upper panel) and daily entrainment (with 95% CI; lower panel) of rainbow trout (left panels), brown trout (center panels), and mountain whitefish (right panels) in the Carseland Canal, Alberta.

rescues from 1998 to 2000 differed substantially from the 2003 fish rescue and were therefore not included in our analysis. To compare fish rescues between years, all data (including those from this study) were confined to fish caught in the upper 2 km of the canal.

Results

Entrainment into the Canal

Abundance of rainbow trout of all sizes in the upper 10 km of canal was variable throughout the diversion period in 2003 (Figure 3). Abundance peaked in mid-July; 1,181 rainbow trout were estimated to be present in the upper 10 km of the canal. The temporal pattern of entrainment into the canal was reflected in the pattern of abundance. The entrainment rate was low throughout the first half of the canal diversion period and peaked at 155 fish/d in early August. The entrainment rate was lower throughout the rest of the season. Small, negative entrainment estimates were probably the result of measurement errors in abundance determined from gill-net catches and reflected the magnitude of uncertainty in our estimates. Total entrainment of all sizes of rainbow trout in the 2003 diversion period was estimated as 3,996 fish (95% confidence interval [CI] = 2,113–8,696). Of this total, 42% were large (>150 mm) rainbow trout (1,683 fish; 95% CI = 892–3,671).

Abundance of brown trout of all sizes in the canal was low throughout the diversion period until the end of August, after which it was almost always greater than 100 fish (Figure 3). The entrainment rate also reflected this pattern; a maximum of only seven brown trout were entrained per day before August 31 (Figure 3). In the remainder of the diversion period, the entrainment rate was almost always greater than 10 brown trout per day, resulting in an estimated annual entrainment of 664 brown trout (95% CI = 356–1,448). Of this total, 17% were large (>150 mm) brown trout (116 fish; 95% CI = 64–255).

Mountain whitefish abundance of all sizes was also low throughout the early diversion period until August, and abundance until this time never exceeded 300 fish. Abundance was higher in the remainder of the diversion period and peaked in mid-September at 58,434 (Figure 3). The entrainment rate in the canal before August was less than 50 mountain whitefish/d. The entrainment rate for the remainder of the diversion period was high, peaking at 10,007 fish/d (Figure 3). Annual entrainment was estimated at 93,850 mountain whitefish (95% CI = 49,748–202,991). Of this total, 0.5% were large (>150 mm) individuals (430 fish; 95% CI = 230–934).

The second approach for estimating entrainment involved marking fish in the river and sampling in the canal to recapture marked fish that entered the canal. Of the 1,175 rainbow trout, brown trout, and mountain whitefish marked in the river, only one was recovered in the Carseland Canal. This recaptured fish was a 425-mm rainbow trout recovered in early October. It was marked in September at the upstream marking site nearest to the headworks. We were initially surprised at this extremely low recapture rate given the number of fish marked in the Bow River. However, using the discrete-time model (equation 10) with estimated river mortality, canal entrainment, and evacuation rates (Table 1), we would expect a maximum of less than

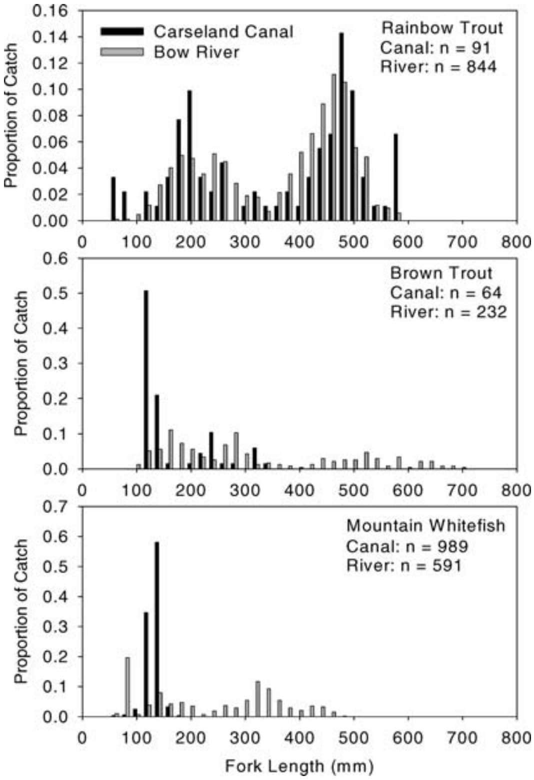

FIGURE 4.—Size structure of rainbow trout, brown trout, and mountain whitefish caught by boat electrofishing in the Bow River and by gill and fyke nets in the Carseland Canal, Alberta.

one river-marked rainbow trout, brown trout, or mountain whitefish to be present on any day in the upper 10 km of the canal. Therefore, it is not surprising that only one river-marked rainbow trout was captured in the canal during the whole irrigation season.

Size-selective entrainment was assessed by contrasting the size-structure of entrained fish caught in the canal with the size-structure of the Bow River population assessed through electrofishing. Size ranges of the entrained and river-resident rainbow trout were similar (Figure 4). The data suggest that the canal selectively entrained small (<150 mm) rainbow trout; however, it is also likely that boat electrofishing in the Bow River also selected against smaller sizes. Better information on the size structure of the Bow River population is necessary to draw stronger inferences about the size selectivity of entrained rainbow trout. These general patterns and caveats also apply to entrained and Bow River brown trout (Figure 4). However, the pattern differed for mountain whitefish (Figure 4). Entrainment of mountain whitefish apparently selected strongly for small fish, but again riverine boat electroshocking probably undersampled small fish.

Population-Level Impacts

The Bow River rainbow trout population (≥150 mm) was estimated to include 186,847 fish in 2001 (95% CI = 180,850–193,000; T.R. and P.A., unpublished data) (Table 2). The annual proportion of the river population of rainbow trout lost to entrainment, which represents the canal-induced annual mortality, was 0.009 (95% CI = 0.005–0.020). Total annual mortality, as estimated from a catch curve of fish caught by electrofishing in 2001, was estimated at 0.788 (95% CI = 0.493–0.912; $n = 4$, $r^2 = 0.97$, $P < 0.05$). Therefore, mortality through entrainment into the Carseland Canal was 1.1% of the total mortality observed for the Bow River rainbow trout population.

The Bow River brown trout population (≥150 mm) was estimated at 25,001 fish in 2001 (95% CI = 23,300–27,075; T.R. and P.A., unpublished data) (Table 2). The annual proportion of the river population of brown trout lost to entrainment, which represents the canal-induced annual mortality, was 0.005 (95% CI = 0.002–0.011). Total annual mortality, as estimated from a catch curve of fish caught by electrofishing in 2001, was estimated at 0.599 (95% CI = 0.023–0.835; $n = 4$, $r^2 = 0.91$, $P < 0.05$). Therefore, mortality through entrainment into the Carseland Canal was 0.8% of the total mortality observed for the Bow River brown trout population.

The Bow River mountain whitefish population (≥150 mm) was estimated to be 301,173 in 2001 (95% CI = 291,600–313,300; T.R. and P.A., unpublished data) (Table 2). The proportion of the river population of mountain whitefish lost to entrainment (i.e., the canal-induced annual mortality) was 0.001 (95% CI = 0.001–0.003). Total annual mortality, as estimated from the 2001 electrofishing catch curve, was 0.362 (95% CI = 0.011–0.598; $n = 4$, $r^2 = 0.90$, $P < 0.05$). Therefore, mortality through entrainment into the Carseland Canal was 0.3% of the total mortality observed for the Bow River mountain whitefish population.

Timing and Correlates of Entrainment Rate

Entrainment rate was variable across the 12 periods from the beginning to end of the 2003 diversion period (Figure 3). Assessment of cumulative entrainment by species shows that the majority of entrainment occurred during the second half of the diversion period (Figure 5). The majority of entrained rainbow trout preceded the majority of entrainment for the other target species. Eighty percent of the rainbow trout entrainment occurred after July 21, whereas August 23

TABLE 2.—Estimates (95% CI) of the abundance of large (≥150 mm) rainbow trout, brown trout, and mountain whitefish in the Bow River, Alberta; total annual mortality; entrainment into the Carseland Canal; and canal-induced annual mortality.

Species	Abundance in Bow River (*N*)[a]	Total annual mortality	Entrainment in canal (*N*)	Canal-induced annual mortality
Rainbow trout	186,847 (180,850–193,000)	0.788 (0.493–0.912)	1,683 (932–3,481)	0.009 (0.005–0.020)
Brown trout	25,001 (23,300–27,075)	0.599 (0.023–0.835)	116 (67–243)	0.005 (0.002–0.011)
Mountain whitefish	301,173 (291,600–313,300)	0.362 (0.011–0.598)	430 (240–889)	0.001 (0.001–0.003)

[a] T.R. and P.A., unpublished data.

and September 3 marked equivalent entrainment for brown trout and mountain whitefish, respectively.

Temporal variation in entrainment rate was not correlated with discharge or river water temperature for any of the target species (Pearson's correlation coefficient r^2: $n = 13$ time periods; $P > 0.05$) (Figure 6).

Interannual Variation in Entrainment

In 2003, the number of rescued fish accounted for 1.3, 22.1, and 2.5% of the rainbow trout, brown trout, and mountain whitefish estimated to be entrained throughout the complete diversion period. Assuming constancy of the ratio of fish caught at the cessation of the irrigation season to total annual entrainment, annual entrainment from 2001 to 2003 varied eightfold for rainbow trout and brown trout (Table 3). Estimated entrainment was the lowest for these two species in 2003. In contrast, total annual entrainment of mountain whitefish varied threefold, and 2003 was the year with highest estimated entrainment. Assuming the same ratio of small (<150 mm) and large fish (≥150 mm) across years, estimated percent of total annual mortality caused by entrainment for rainbow trout was 9.2, 8.1, and 0.9% in 2001, 2002 and 2003, respectively. Estimated total annual mortality caused by entrainment for brown trout was 1.2%, 3.4% and 0.5% in 2001, 2002 and 2003, respectively. Total annual entrainment mortality for mountain whitefish was 0.13% in 2001, 0.12% in 2002, and 0.14% in 2003.

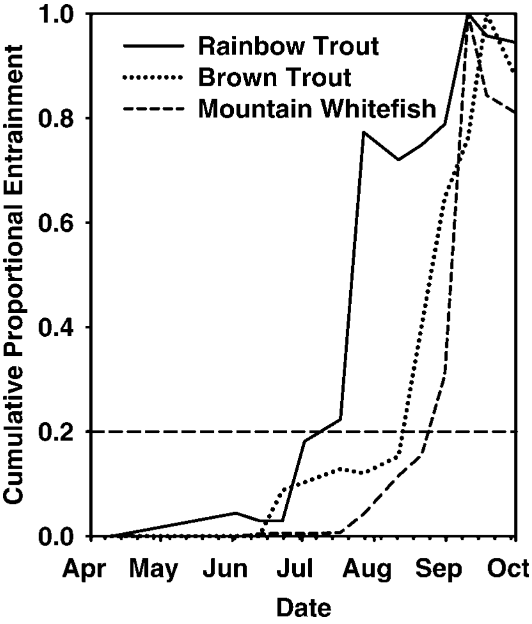

FIGURE 5.—Cumulative proportional entrainment of rainbow trout, brown trout, and mountain whitefish in the Carseland Canal, Alberta, over the irrigation diversion season.

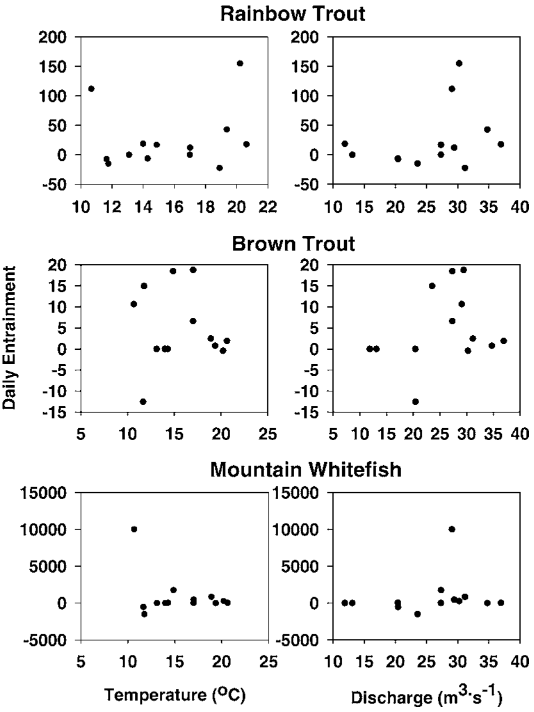

FIGURE 6.—Relations between rainbow trout, brown trout, and mountain whitefish daily entrainment and river temperature at the Carseland Canal (Bow River, Alberta) headworks (left panels) or discharge into the canal (right panels).

TABLE 3.—Fish rescue catch and estimated total entrainment of rainbow trout, brown trout, and mountain whitefish of all sizes in the Carseland Canal, Alberta. Data for the 1998–2002 fish rescue are from Eisler and Brewin (2002) and Eisler et al. (2003).

	Rainbow trout		Brown trout		Mountain whitefish	
Year	Fish rescue catch	Estimated entrainment[a]	Fish rescue catch	Estimated entrainment[a]	Fish rescue catch	Estimated entrainment[a]
1998	310		1,366		86,096	
1999	407		818		23,419	
2000	1,585		449		64,564	
2001	412	32,281[b]	222	1,003[b]	790	31,523[b]
2002	360	28,207[b]	1,074	4,853[b]	719	28,690[b]
2003	51	3,996[c]	147	664[c]	2,352	93,850[c]

[a] Total entrainment could not be estimated from fish rescue catch in 1998–2000 because methods deviated substantially from those used in 2001–2003.

[b] Entrainment for 2001–2002 was estimated with the assumption that the ratio of the fish rescue catch to the entrainment estimate was the same as in 2003.

[c] Entrainment was estimated from the abundance and evacuation method explained in the text.

Nontarget Species

Fourteen species of fish were caught in the Carseland Canal and settling pond in 2003. The three species of sport fish that we targeted were only a small proportion of the total number of individuals captured (Table 4). By far, the most abundant group of fish caught in the canal and settling pond were the catostomids (primarily longnose suckers and white suckers), representing about 70–80% of the fish captured in all three of the sampling methods. The large proportion of brook sticklebacks caught in the fyke nets, which were predominately set in the settling pond, suggests that a resident population exists there. Other species caught in fyke nets or gill nets or during the fish rescue, including fathead minnow, longnose dace, mountain suckers, trout-perch, and yellow perch, may also maintain resident populations in the settling pond or may simply represent canal entrainment.

Discussion

The Carseland Canal entrained thousands of rainbow trout, brown trout, and mountain whitefish from the Bow River during the 2003 diversion season. The temporal pattern of entrainment was variable, but the majority of the entrainment was in the second half of the season for all three species. Fish of a broad range of sizes were entrained. Rainbow trout appeared to be entrained in proportion to their abundance by size in the Bow River, but entrainment of brown trout and mountain whitefish appeared to be selective of smaller individuals. A more quantitative assessment of size selectivity is not possible because of uncertainties in the effectiveness of the Bow River sampling for small fish. Other studies have also documented the loss of salmonids from streams and rivers into irrigation canals (Clothier 1953, 1954; Spindler 1955; Stober et al. 1983; Reiland 1997; see review in Earle and Post 2001). Our results suggest that entrainment rates are not simply a function of river discharge into the canal. It also does not appear to be related to seasonal patterns in spawning migrations. Adult rainbow trout were the most abundant large fish to be entrained, and their spawning migrations are concentrated during April–June; however, entrainment was concentrated within the last 2 months of the diversion season. Brown trout and mountain whitefish may initiate spawning migrations during the period of peak entrainment, but the majority of the individuals entrained were immature.

Our analysis shows that the evacuation rate (11% per day) in a relatively uniform irrigation canal can be rapid; the rate implies an average residence time for entrained fish of only 9 d in the upper 10 km of canal. In contrast, Cooke et al. (2004) found smallmouth bass *Micropterus dolomieu* wintering within a thermal discharge canal on Lake Erie. Different evacuation rates among canals will have obvious and profound implications to the interpretation of capture data collected from canals. Canals with low evacuation rates will accumulate (i.e., integrate) fish across the entrainment season; whereas, canals with high evacuation rates will tend to be devoid of fish except in days immediately after an entrainment event. For example in the Carseland Canal, one half of a cohort entrained at a particular time is expected to be flushed from the upper 10 km within 6.3 d. It follows that a capture study from canals with low evacuation rates will always recover more fish than high evacuation-rate canals even if all canals entrain fish at the same rate. Furthermore, a tagging study where fish are marked in the donor population and recaptured in the canal cannot be used to differentiate entrainment rates among canals, as canals with low fish evacuation rates have higher recapture probabilities (i.e., fish are available for recapture for more days). Therefore, there is little utility in comparing numbers of fish captured among different canals (or in different seasons) to infer

TABLE 4.—Species composition (%) of fish of all sizes captured in the Carseland Canal, Alberta, during 2003 in gill nets, fyke nets, and the fall fish rescue (seining and electrofishing).

Species	Species composition (%)[a]		
	Gill net	Fyke net	Fish rescue
Brook stickleback *Culaea inconstans*	0.03	18.51	1.27
Brown trout	2.24	<0.01	0.39
Burbot *Lota lota*	0.03		<0.01
Fathead minnow *Pimephales promelas*	0.03	1.25	0.02
Lake chub *Couesius plumbeus*			0.02
Longnose dace *Rhinichthys cataractae*	0.03	0.25	3.08
Longnose sucker *Catostomus catostomus*	19.22	11.54	59.34
Mountain sucker *Catostomus platyrhynchus*		0.19	0.03
Mountain whitefish	28.10	0.50	16.69
Northern pike *Esex lucius*	0.07	<0.01	
Rainbow trout	1.71	0.03	0.23
Trout perch *Percopsis omiscomaycus*		0.08	0.01
White sucker	48.30	67.60	18.91
Yellow perch *Perca flavescens*	0.21	0.04	0.01
All (*N*)	2,861	93,089	54,598

[a] A value of "<0.01" means that the species was present but represented less than 0.01% of the total catch.

entrainment rates unless an assumption of similar evacuation rates can be supported.

The proportion of total mortality observed in the Bow River populations that can be explained by canal-induced mortality was small in 2003. This conclusion depends on the assumption that the Bow River populations are spatially homogeneous throughout the 170-km section of the lower Bow River coldwater fishery. This assumption is reasonable, particularly for rainbow trout, which spawn primarily in a single tributary, the Highwood River (Rhodes 2005), and disperse throughout this section (Figure 1). If subpopulations of brown trout and mountain whitefish are spatially distinct within this section of the river, then our estimates of the proportion of total mortality explained by canal entrainment may be underestimated at the local scale. Stream salmonid losses into irrigation canals may involve as much as several percentage points of the donor stream populations (Reiland 1997).

Estimates in the abundance of sport fish in the canal at the end of the diversion season suggest that entrainment may vary from three to eightfold among years. It is unclear whether this variation is due to within season variability in entrainment coupled with the cessation of water diversion or represents interannual variability in entrainment from the Bow River. If the latter is true, then our estimates of the proportion of total mortality explained by canal entrainment may be as much as eightfold higher for rainbow and brown trout. Unfortunately, we have no way to differentiate between within-season or annual variance in fish rescue catches and how these sources of variation reflect on total annual entrainment. Additional information on interannual variance in canal-induced mortality would be useful. If our results for 2003 are representative, then it can be argued that canal-induced mortality is only a small component of observed natural and fishing mortality. If indeed our crude estimates of interannual variability are representative, then canal mortality becomes a much larger proportion of total mortality.

Although the emphasis of this study was on three species of sport fish, it is clear that the majority of entrainment into the canal was for two species of *Catostomus*. Unfortunately, we have no data on their abundance or size-structure in the donor Bow River population and we cannot comment on population-level impacts from their entrainment. Furthermore, the loss of fish biomass exports nutrients from the donor river, potentially altering ecosystem structure and function.

In conclusion, substantial numbers of catchable-sized sport fish were lost from the Bow River in 2003. From the standpoint of recreational fisheries management, the losses in 2003 were a small portion of total annual mortality. Uncertainties surrounding interannual variability temper this conclusion because entrainment rates of rainbow trout and brown trout may have been atypically low in 2003. In addition, the Carseland Canal is the largest, but not the only, diversion on the Bow River. Population-level impacts are certainly cumulative over all sources of entrainment loss. Finally, our results show that installation of screening or other barrier devices to reduce entrainment will have the greatest benefit if functional during the second half of the diversion season. Since the majority of entrained fish were small (<150 mm), the device should be effective on these smaller fish sizes to eliminate entrainment. Fishery and water managers will have to weigh the full costs and benefits of screening to the water supply and the recreational fishery.

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