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North American Journal of Fisheries Management

ISSN: 0275-5947 (Print) 1548-8675 (Online) Journal homepage: http://www.tandfonline.com/loi/ujfm20

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Geoffrey A. McMichael , Anthony L. Fritts & Todd N. Pearsons

To cite this article: Geoffrey A. McMichael , Anthony L. Fritts & Todd N. Pearsons (1998) Electrofishing Injury to Stream Salmonids; Injury Assessment at the Sample, Reach, and Stream Scales, North American Journal of Fisheries Management, 18:4, 894-904, DOI: 10.1577/1548-8675(1998)018<0894:EITSSI>2.0.CO;2

To link to this article: http://dx.doi.org/10.1577/1548-8675(1998)018<0894:EITSSI>2.0.CO;2

Published online: 08 Jan 2011.

North American Journal of Fisheries Management 18:894–904, 1998

Electrofishing Injury to Stream Salmonids; Injury Assessment at the Sample, Reach, and Stream Scales

GEOFFREY A. MCMICHAEL,* ANTHONY L. FRITTS, AND TODD N. PEARSONS

Washington Department of Fish and Wildlife
600 Capitol Way North, Olympia, Washington 98501, USA

Abstract.—Electrofishing injury rates in rainbow trout and juvenile steelhead *Oncorhynchus mykiss* and juvenile spring chinook salmon *O. tshawytscha* were quantified in samples collected in four tributaries to, and one reach of, the Yakima River, Washington. Estimated electrofishing injury rates at the reach and stream scales were generated by using sample injury rates, derived from this study, multiplied by capture probabilities and the fraction of habitat sampled. Sample injury rates in small *O. mykiss* and juvenile spring chinook salmon were low. Mean electrofishing injury rate in *O. mykiss* samples captured in tributaries was 5.1%. Only 2.0% of the juvenile spring chinook salmon captured by electrofishing in the Yakima River were injured. Larger *O. mykiss* (≥250 mm fork length, FL) were injured at a significantly higher rate (27.7%) than their smaller counterparts (1.2%; $P = 0.023$) in the Yakima River sample. Electrofishing injury rates decreased with increasing scale from the sample to the reach and stream scales. Injury rates for index reaches that we use for long-term monitoring were 4.9% for *O. mykiss* in tributaries, 0.7% for *O. mykiss* less than 250 mm FL in the Yakima River, and 11.2% for *O. mykiss* larger than 250 mm FL in the Yakima River. Although the injury rate at the reach scale for larger *O. mykiss* was relatively high, we do not believe it affects our long-term monitoring data because annual mortality of these fish is high (>60%) and because a small proportion of the total population is captured by electrofishing (18–21%). Stream scale injury rates were very low in tributaries (0.1%) and in the Yakima River for smaller *O. mykiss* (a mixture of juvenile steelhead and resident rainbow trout <250 mm FL; 0.1%). The estimated stream scale injury rate for larger *O. mykiss* (≥250 mm FL) was 2.1%. Stream scale injury rates for all groups examined were below levels that we would expect to affect our long-term monitoring data. The distribution, conservation status, size structure, lifespan and annual mortality of the population, the fraction of the habitat sampled, sampling frequency, and availability, effectiveness, and cost of alternative sampling methods, must all be balanced against the need for data when establishing research or monitoring efforts that use electrofishing.

Electrofishing has been widely used by fisheries researchers and managers for more than 50 years to collect fish and monitor fish populations. During the history of electrofishing, there have been many advancements in gear and methods that have increased the capture probability of fish in various environments (Taylor et al. 1957; Bird and Cowx 1993; Burkhardt and Gutreuter 1995; Cunningham 1995; Miranda et al. 1996). Deleterious effects of electrofishing on the sampled fishes were recognized by some researchers more than 40 years ago (Hauck 1949; Pratt 1955), but it was not until relatively recent times that gear and methods have been refined to decrease electrofishing injury and mortality to fish (Sharber et al. 1994). With some native North American fish populations at critically low levels (e.g., Williams et al. 1989; Nehlsen et al. 1991), managers must weigh the potential management or scientific benefits of obtaining fish data by electrofishing against the risks of harming fish populations.

As certain stocks of Pacific salmonids *Oncorhynchus* spp. become more imperiled in the northwestern United States (Nehlsen et al. 1991), the potential adverse effects of sampling these populations with any potentially harmful method must be evaluated. Injuring or killing fish by sampling them is considered a ''taking'' under the Federal Endangered Species Act. Electrofishing has been singled out as an activity that will not be granted a research exemption in areas containing threatened or endangered coho salmon *O. kisutch* (USOFR 1997). Electrofishing may still be permitted under the Federal Endangered Species Act if certain procedures are followed.

In addition to potential effects on rare or sensitive species, electrofishing may cause injuries to fish that may affect long-term population monitoring programs, such as the one we are involved with in the Yakima River basin. If electrofishing injury significantly affects one or more response

* Corresponding author: mcmicgam@dfw.wa.gov

variables being monitored in a given population, then the value of the data collected for determining the effects of specific management actions will be markedly reduced.

The majority of the existing literature on electrofishing injury focuses on injury at the scale of individual fish (sample), with some notable exceptions (Schill and Beland 1995; Kocovsky et al. 1997). Social values associated with electrofishing injury at the sample scale are primarily ethical; esthetic concerns are also present because of the appearance of an injured fish. Electrofishing injury at the monitoring site or reach scale (all fish within the total area sampled) may affect the results of research that managers use to make resource decisions. Population scale (e.g., all fish in a stream) injury caused by electrofishing becomes more of a conservation and stewardship issue. Schill and Beland (1995) recommended viewing electrofishing injury from a population perspective. However, all three scales—sample, reach, and stream—are important. The stock status, value to humans, and value to the ecosystem of a particular fish population, as well as the educational and management values of the sampling of that population, should all be considered when determining acceptable electrofishing injury rates.

As part of an ongoing research effort in the Yakima River basin, Washington, that relies heavily on data collected by electrofishing, we have examined the effects of certain electrofisher settings on the potential to adversely affect the fish we sample (McMichael 1993). To further examine the possibility that our data collection efforts were affecting fishes in various environments within the Yakima basin, we initiated the current study in 1995. We had concerns about electrofishing injuries related to our monitoring program because we observed external ''bruises'' attributed to electrofishing in an average of 2.6% of the rainbow trout and juvenile steelhead *O. mykiss* that we collected from the Yakima River between 1990 and 1995 (WDFW, unpublished data). Some of the bruised fish were unable to swim when released. Further, data presented by Kocovsky et al. (1997) showed that external bruises provided an underestimate of actual spinal injury due to electrofishing.

Our primary objective in this study was to determine if our electrofishing methods cause significant harm to upper Yakima River juvenile steelhead, resident rainbow trout, or juvenile spring chinook salmon *O. tshawytscha* at the sample, reach, or stream scales. From the perspective of resource stewardship, we were concerned that the critically low population level of upper Yakima River steelhead might be affected by electrofishing. We were also concerned about potential effects to current monitoring programs for *O. mykiss* and spring chinook salmon. Individual effects to larger resident rainbow trout were also of concern due to the popularity of the recreational fishery and the potential for these larger fish to have multiple exposures to electrofishing. Specifically, we wanted to learn what percentages of smaller rainbow trout or juvenile steelhead (<250 mm fork length, FL), adult resident rainbow trout (≥250 mm FL), and juvenile spring chinook salmon (<150 mm FL) were injured as a result of being collected with the electrofishing equipment and settings we typically use in the Yakima River and its tributaries. These data were then combined with existing data to assess the rates of electrofishing injury in our annually sampled index reaches and in entire streams.

Methods

Study area.—All sampling was conducted in the Yakima River basin, a tributary to the Columbia River, upstream from Roza Dam (Figure 1). Samples were collected from reaches (100–400 m long) of four tributaries (West Fork of the Teanaway River, and Swauk, Taneum, and Naneum creeks) and one 6-km section of the Yakima River (from Umtanum Creek to Wymer in the canyon between the cities of Ellensburg and Yakima, Washington). Tributaries were selected to represent the range of environmental conditions present in the upper Yakima River basin (Table 1).

Field and laboratory procedures.—We used a control–treatment design to determine the effects of electrofishing on spinal injury in juvenile steelhead, rainbow trout, and juvenile spring chinook salmon. In tributaries and the Yakima River, control fish were captured by angling with artificial flies and lures before the collection of treatment fish with electrofishing equipment. We assumed that angling would not produce spinal injuries. To minimize our chances of collecting fish that we had electrofished in previous surveys, all samples were collected in areas where we had not electrofished within the previous 4 years (the typical life span of *O. mykiss* in these areas; Martin and Pearsons 1994). The electrofishing equipment and methods used in this work were the same as those used in our routine sampling in the tributaries and the Yakima River (except that fish for this study were killed, while our routine surveys call for the live release of all fish). Tribu-

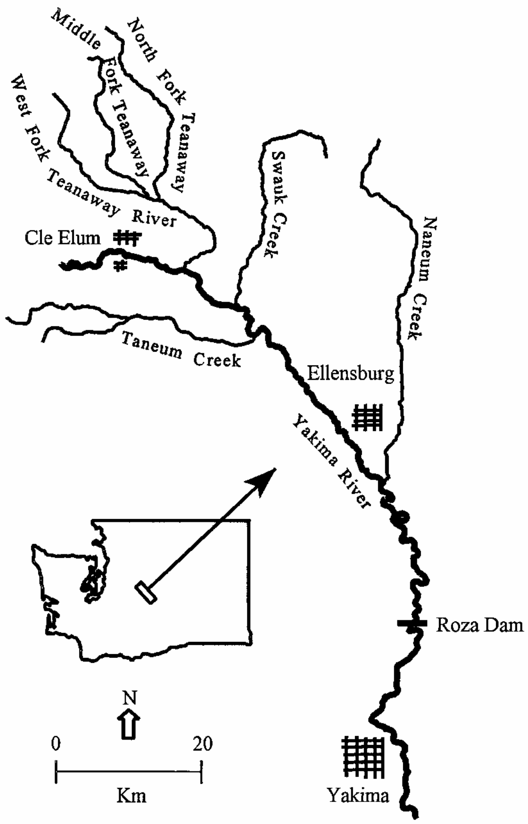

FIGURE 1.—Map of the study area, showing the Yakima River and associated tributaries where the electrofishing injury research was conducted.

taries were sampled during daylight with a battery-powered Smith Root model 12 backpack electrofisher with a 28-cm-diameter aluminum ring anode and a 305-cm-long cable cathode. Settings for all tributary sampling were 300-V, 30-Hz pulsed DC (12.5% duty cycle). Fish collected in this study were removed on only one pass; our typical population sampling of 100-m-long index sites require two or three passes (estimate is based on ≥50% depletion; Zippin 1958).

The Yakima River was sampled from a 5.1-m fiberglass drift boat with a stationary ''Wisconsin ring'' anode (102-cm-diameter, with 20 46-cm-long cable droppers, each 0.6 cm in diameter) suspended from the bow by a boom and a 30-cm × 3.7-m aluminum cathode attached to the hull. The boat electrofisher was powered by a 3,500-W generator and a Coffelt Mark XXII rectifier set for the ''complex pulse system'' (see Sharber et al. 1994 for details on the output of this setting). Electrical output from the boat electrofisher, as registered on the meters, was 450 V and 7 A. This is the same sampling protocol that we use to conduct annual mark–recapture population estimates (methods similar to Vincent 1971) in the Yakima River. All samples collected in the Yakima River for this study were captured on one pass; actual population estimates require two passes (one marking pass and one recapture pass a week later).

All fish were kept alive in holding vessels until we were finished sampling. Control fish were subjected to the same degree of postcapture handling as treatment fish. Fish were killed in a lethal concentration (0.5 mg/L) of tricaine methanesulfonate (MS-222), weighed to the nearest gram, measured to the nearest millimeter FL, and visually examined for external electrofishing bruises (Horak and Klein 1967). Each fish was placed in a resealable plastic bag, which was labeled with fish length and weight, notes, and a unique number, and held on ice in a cooler. Upon returning from the field, the fish were immediately frozen until they were X-rayed.

Partially thawed fish were X-rayed with a MinX-ray model 300 X-ray unit set at 30–60 kV, at a distance of 61 cm from the plate for a 1.5 s exposure on 3M 1413 standard veterinary X-ray film. Each fish was X-rayed both laterally and dorsoventrally with an X-ray marker that displayed a randomly assigned number. All fish were frozen again after being X-rayed for later necropsies.

The X-ray plates were shuffled, and skeletal im-

TABLE 1.—Physical characteristics for four tributaries and one section of the Yakima River and dates in 1995 when treatment and control samples for electrofishing injury research were collected.

Stream	Length (km)	Aspect	Water temperature (°C)	Conductivity (*mS*/cm)	Discharge (m^3/s)	Collection date
Naneum Creek	52	S		70		Sep 21
Swauk Creek	34	S	16	140	0.05	Sep 19
Taneum Creek	39	NE	11	150	0.28	Sep 20
West Fork Teanaway River	24	E	18	100	0.10	Sep 18
Yakima River	315	SE	18	130	39.80	Oct 18

ages were examined for the presence of spinal injuries with an X-ray reader and a loupe (8× magnification). All examinations of X-ray plates and necropsies were done without the knowledge of whether the fish was a control or treatment fish. Spinal injuries detected on X-ray plates were rated by severity (0 = none apparent; 1 = compression of vertebrae; 2 = misalignment and compression of vertebrae; 3 = fracture of one or more vertebrae or complete separation of 2 or more vertebrae; see Reynolds 1996 for details). Number of vertebrae, location, severity, and whether the injury was visible on dorsal or lateral views (or both) were recorded. All fish that showed any possibility of spinal injury on X rays were partially thawed and necropsied. The musculature was filleted away from the spine on both sides, and the spinal column and surrounding tissue was examined to determine whether the injury appeared to have been caused by the sampling event in which the fish was captured or whether it was an old healed injury or natural spinal abnormality (McCrimmon and Bidgood 1965; Gill and Fisk 1966; Sharber and Carothers 1988). Necropsies were also used to evaluate the extent of hemorrhaging in musculature surrounding the spinal column (McMichael 1993). When X rays alone were inconclusive, necropsy results were the final determinant on whether we considered a fish injured by our sampling. If a fish showed displacement, compression, or fusion of vertebrae on the X ray but did not show any related hemorrhages when filleted, then it was assumed to be either an old injury or a natural deformity and was not classified as a sampling injury caused during this experiment (McCrimmon and Bidgood 1965; Sharber and Carothers 1988). Hemorrhages were also rated by apparent severity (0 = no hemorrhage; 1 = wounds separate from spine; 2 = wounds on spine ≤ width of 2 vertebrae; 3 = hemorrhages on spine > width of 2 vertebrae; Reynolds 1996). Spinal injury ratings were used unless the X rays were equivocal, then hemorrhage ratings from necropsies were used. Not all fish were necropsied; therefore, we may have underestimated hemorrhages. Injury rates are thus a combination of the results from both techniques. However, each fish was classified as either injured by our sampling or not.

Injury rate estimations for tributaries.—Our first step was to calculate injury rate (percentage) at the sample scale from individual fish captured at each site (sample). To determine the rate of injuries in treatment fish that were the result of our electrofishing, we subtracted the rate of injuries observed in each control group from the rate of injuries observed in each treatment group. These differences between the injury rates in control and treatment groups are estimates of electrofishing injury rates at the sample scale.

To determine injury rates at the reach and stream scales, we used data we have collected on capture probabilities (from multiple-removal population estimates) and the fraction of habitat that we sample annually in our monitoring program. Specifically, we wanted to know what percentage of all *O. mykiss* within our index reaches were likely to be injured as a result of our electrofishing efforts. To estimate injury rates among fish within index reaches in tributaries we used the following equation:

$$I_t = E_t[1 - (1 - C)^n]; \qquad (1)$$

I_t = percent of *O. mykiss* within tributary index reach t injured during a single multiple-removal population estimate, E_t = sample injury rate in tributary t, C = capture probability, and n = number of electrofishing passes. Capture probabilities were available from several index reaches in the same or adjacent tributaries to the ones sampled in this study (1990–1995) and were calculated by the Microfish program for multiple-removal population estimates (Van Deventer and Platts 1985).

To provide a stream scale injury rate estimate, we multiplied I_t by the fraction of habitat that we sampled in tributaries. The fraction of habitat sampled was calculated for each tributary by dividing the stream length (km) sampled each year by the length of the tributary. Assumptions for the tributary models include (1) all injured fish are captured in the pass they are injured (i.e., exposed but not captured fish are uninjured), (2) additional exposures do not increase E_t, (3) capture probability (of the remaining fish) is the same on all passes, and (4) fish density is the same inside the index reach as it is outside the index reach. If our assumptions are true, this produces what we believe is a high (i.e., worst-case) estimate of the electrofishing injury we might cause in tributary *O. mykiss* populations as a result of sampling. If assumptions 1 or 2 are wrong, then a low estimate would be produced. If assumptions 3 or 4 are wrong, the direction of the bias would be influenced by the way in which the assumptions were violated.

Injury rate estimations for the Yakima River.—To estimate electrofishing injury rates in the Yakima River, we used different models to account for the differences in sampling methodology and size-classes of *O. mykiss* collected. In index reaches that are sampled annually, we estimated annual injury rates for fish divided into two size-classes. The following equation estimates the percentage of a specific size-class of *O. mykiss* that are injured within an index reach of the Yakima River in one season:

$$I_s = n(E_s C_s); \qquad (2)$$

I_s = percent of *O. mykiss* of size-class s in the main-stem index reach that are injured in one season, n = the number of exposures (i.e., one mark pass and one recapture pass = 2), E_s = percent of *O. mykiss* of size-class s that are injured on one electrofishing pass, and C_s = capture probability for *O. mykiss* of size s in each pass (as determined by mark–recapture methodology; Vincent 1971). This equation assumes that two electrofishing passes (one mark pass and one recapture pass) double the proportion of injured *O. mykiss*. As opposed to the tributary model, in which fish are removed from the site after they are captured and are not susceptible to electrofishing in subsequent passes, all fish captured in the Yakima River index reaches are marked and released back into the same section and are present during the subsequent electrofishing pass. This is the reason why the value for EC doubles in Yakima River reaches instead of changing the way it does in tributary index reaches (equation 1). Population estimates and capture probabilities for each size-class were available from our monitoring program mark–recapture population estimates for five sections of the Yakima River (1991–1995). To estimate the percentage of all *O. mykiss* within an index reach in the Yakima River that would be injured by one year's electrofishing (I_m) we used the following equation:

$$I_m = \sum_{s=1}^{n} (I_s P_s); \qquad (3)$$

I_s = reach injury rate for fish of size-class s; P_s = proportion of the population made up by fish of size-class s.

To expand the injury rate estimate to the stream scale in the Yakima River, we multiplied I_m by the fraction of habitat we sample each year. The fraction of habitat we sampled for the Yakima River was calculated by dividing the total number of kilometers we sample annually (22 km in five discrete sections) by the distance between Roza and Easton dams (119 km). The habitat-based expansion assumes that mean *O. mykiss* density outside the index reaches equals the mean density within the index reaches.

Statistical procedures.—Fork lengths of fish in control and treatment groups were compared by means of two-sample t-tests. Standard deviations for injury rates of experimental groups were calculated by applying the procedure for determining assumed standard deviations for binomial distributions described by Sokal and Rohlf (1981). Significance of differences between control and treatment injury rates were determined through the use of one-sided t-tests for differences in proportions. Logistic regressions were performed independently on control and treatment groups of *O. mykiss* to plot the relationship between injury and fish length. We used a chi-square test based on the logistic regression model to test for effects of fish length-group (<250 mm FL or ≥250 mm FL) and control–treatment group on injury to *O. mykiss* collected in the Yakima River.

Results

In all, 396 fish (95 control, 301 treatment) were X-rayed. Mean fork length of control samples were longer in five of seven experimental groups and were significantly longer in four of those groups (Table 2).

Injury rates in treatment groups were higher in six of seven experimental groups; however, only for *O. mykiss* 250 mm FL and longer was this difference significant (Figure 2). Electrofishing injury rates were relatively low in tributaries where *O. mykiss* were generally shorter than 250 mm FL (mean difference between control and treatment = 5.1%) and for smaller *O. mykiss* (mean difference = 1.2%) and juvenile spring chinook salmon (mean difference = 2.0%) collected in the Yakima River (Figure 2). However, a relatively high proportion (mean difference = 27.7%) of the larger *O. mykiss* collected in the Yakima River were injured. Regardless of the collection method or species, injury rates were relatively low in small fish (<250 mm FL) and higher in larger fish (≥250 mm FL). When all *O. mykiss* samples from treatment groups were pooled to examine the relationship between fish length and incidence of injury, we found that larger *O. mykiss* (≥250 mm FL) were injured at a higher rate than their smaller (<250 mm FL) counterparts ($\chi^2 = 7.55$, $P = 0.023$). Similarly, fish length was positively related to incidence of injury in treatment *O. mykiss* (Figure 3; $P < 0.001$). In control samples, injury also increased with increasing fish length but not in a

TABLE 2.—Sample sizes (*N*) and means, ranges, and standard deviations of fork lengths (FL) for salmonids collected in tributaries to, and the main stem of, the Yakima River in 1995. Treatment samples were collected by electrofishing, control samples were collected by angling. The *P*-values for *t*-tests comparing lengths of control and treatment groups are also shown. An asterisk denotes significant difference at $P < 0.05$; WFT = West Fork of the Teanaway River, SPC = spring chinook salmon.

Stream or group	Control			Treatment			
		FL (mm)			FL (mm)		
	N	Mean (range)	SD	*N*	Mean (range)	SD	*P*
Tributaries							
Naneum	10	205 (161–250)	27	25	148 (108–227)	34	<0.001*
Swauk	13	171 (121–250)	34	25	145 (119–207)	24	0.008*
Taneum	19	163 (121–195)	20	25	156 (108–207)	31	0.383
WFT	10	187 (126–261)	37	25	141 (95–196)	25	<0.001*
Yakima River							
O. mykiss							
<250 mm	11	232 (198–245)	14	78	191 (98–247)	48	0.005*
≥250 mm	23	299 (251–356)	37	22	315 (253–376)	39	0.144
SPC	9	111 (104–120)	6	101	117 (98–138)	7	0.017*

statistically significant manner (Figure 3, $P = 0.265$).

Spinal injuries occurred with greater frequency in treatment fish than in control samples (Table 3). The majority of the spinal injuries that were detected in treatment samples were classified as class 2 (misalignment and compression of vertebrae). Similarly, hemorrhages occurred with greater fre-

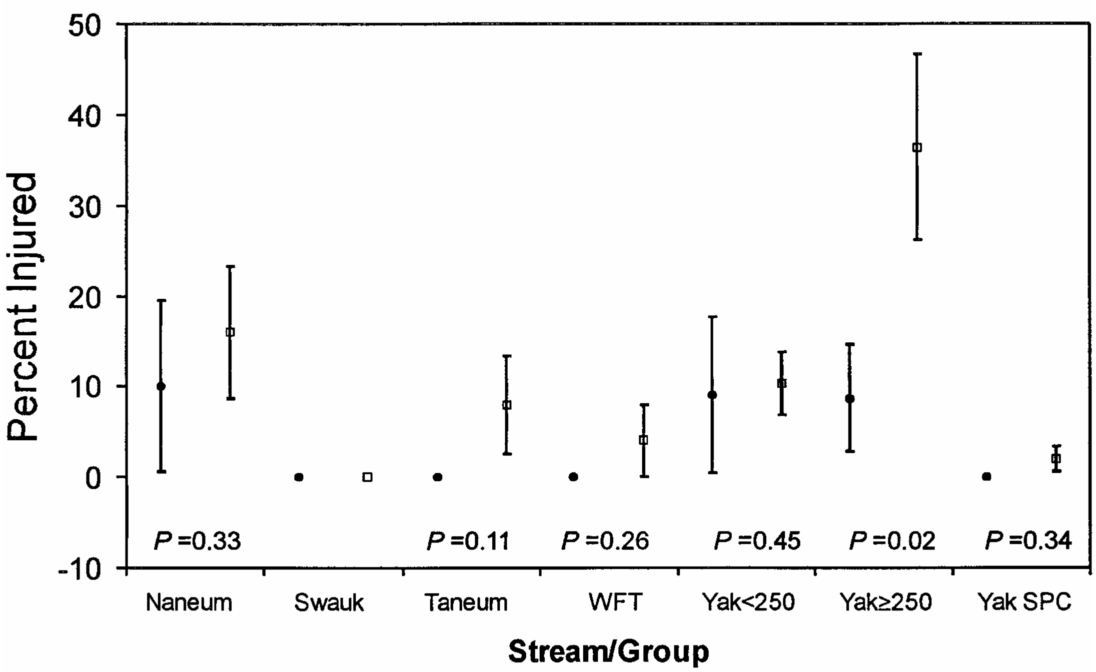

FIGURE 2.—Percent of electrofishing-induced injuries (mean ± SD) detected in control (closed circle) and treatment (open square) rainbow trout, steelhead, and spring chinook salmon captured by electrofishing in tributaries to, and the main stem of, the Yakima River in 1995. The *P*-values for *t*-tests between treatment and control groups are shown below each experimental pair; WFT = West Fork Teanaway River, Yak<250 = *O. mykiss* less than 250 mm FL from the Yakima River, Yak≥250 = *O. mykiss* 250 mm FL or greater from the Yakima River, Yak SPC = juvenile spring chinook from the Yakima River.

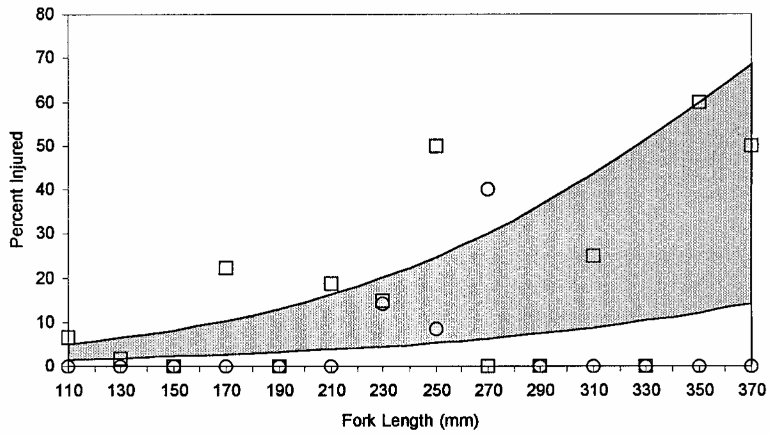

FIGURE 3.—Percent electrofishing injuries of *O. mykiss* versus fork length (mm) in the Yakima River and tributaries in 1995. Treatment (open rectangle, $N = 196$) and control (open circle; $N = 86$) data points are shown, as well as treatment (upper) and control (lower) lines fitted to the data by logistic regression. The shaded area between the fitted treatment and control lines represents the injury due to electrofishing.

quency in fish that had been exposed to electrofishing than in those that were captured by angling; however, only a very small sample of control fish were necropsied. All of the hemorrhages that were observed in control samples were classified as class 2 (wounds on spine ≤ width of 2 vertebrae), while the most common classification in treatment samples was class 3 (wounds on spine > width of 2 vertebrae).

Spinal injuries were not observed in control fish in three of the four tributaries sampled. Both size-groups of control *O. mykiss* collected in the Yakima River, however, showed minor spinal injuries in about 9% of each sample (Figure 2).

Electrofishing injury rates to sampled *O. mykiss* decreased with increasing spatial scale (Table 4). In tributaries, an average of 5% of the *O. mykiss* sampled were injured by electrofishing. To estimate the injury rate within the index reach (equation 1), we used the model that incorporated the average capture probability in multiple-removal population estimates within our 100-m-long index reaches between 1990 and 1995 (68.7%; WDFW, unpublished data). Based on this capture probability data, predicted annual electrofishing injury rates were 4.6% for two-pass estimates and 4.9% for three pass estimates. Further expansions of tributary data are based on three-pass estimates. Estimated annual electrofishing injury rate at the tributary scale for three-pass estimates was 0.1% (Table 4) because only 1.1% of the tributary habitat was electrofished.

In the Yakima River, the only significant difference between control and treatment samples was in the group of larger *O. mykiss*. However, the differences between control and treatment samples

TABLE 3.—Percent frequency of different class ratings of electrofishing-induced spinal injuries and hemorrhages in treatment and control rainbow trout and steelhead in the Yakima River and its tributaries. Injury ratings are as follows: 0 = no injury, 1 = slight injury, 2 = moderate injury, 3 = severe injury. See text for specific criteria for classifications; parenthetical values are sample sizes.

	Control		Treatment	
Class	Spinal injury, % (N)	Hemorrhage, % (N)	Spinal injury, % (N)	Hemorrhage, % (N)
0	95.3 (82)	33.3 (2)	89.3 (175)	43.9 (18)
1	1.2 (1)	0.0 (0)	3.6 (7)	12.2 (5)
2	3.5 (3)	66.7 (4)	6.6 (13)	19.5 (8)
3	0.0 (0)	0.0 (0)	0.5 (1)	24.4 (10)

TABLE 4.—Annual electrofishing injury rate projections for *O. mykiss* in tributaries to, and the main stem of, the Yakima River. Location, mean length (mm FL), sample injury rates (Sample), estimated injury rates within index reaches (reach), and estimated injury at the stream scale (stream) are shown. Tributary estimates are based on a three-pass multiple-removal sampling protocol.

Location and size-class	Sample (%)	Reach (%)	Stream (%)
Tributaries			
All (148 mm)	5.1	4.9	0.1
Yakima River			
Small (191 mm)	1.2	0.7	0.1
Large (315 mm)	27.7	11.2	2.1
All (218 mm)	11.9	4.9	0.9

of fish collected in tributaries and the smaller *O. mykiss* from the Yakima River were consistent. In the Yakima River, 1.2% of the small *O. mykiss* sampled were injured by our single electrofishing pass. Our capture probability on small *O. mykiss* averaged 18.1% in the same area where our fish were collected. Using equation (2), we calculated the index reach electrofishing injury rate for smaller trout to be 0.7% as a result of two electrofishing passes per year. Higher individual injury rate in larger *O. mykiss* (≥250 mm FL) contributed to higher electrofishing injury estimates at the index reach scale. These larger individuals were injured at a rate of 27.7% following a single electrofishing pass, and our capture probability (from annual mark–recapture population estimates in five sections) for fish of that size in that area has averaged 20.7% between 1990 and 1995. Therefore, the estimated annual injury on these larger fish within the index reach was 11.2% (Table 4). To estimate the percentage of all *O. mykiss* within a Yakima River index section that would be injured in one season, we used equation (3) and multiplied the size-specific injury estimates by their respective proportions in the population estimate (small, 59.7%; large, 40.3%). This produced an estimated injury rate for all *O. mykiss* within an index reach of 4.9%.

Because we do not conduct population estimates on juvenile spring chinook salmon, we do not have estimated capture probability data to expand individual injury rates to index reach and stream scales. However, visual estimates of juvenile spring chinook salmon abundance are higher than those for small *O. mykiss* in the Yakima River, and injury rates for the two species are similar. If we assume similar capture probabilities for the two species, reach and stream scale injury rates for juvenile spring chinook salmon are probably equal to or lower than those for small *O. mykiss* in the Yakima River.

Discussion

Expanding sample electrofishing injury rate estimates to the reach and stream scales provides a useful context for evaluating potential magnitudes of sampler-induced effects. High injury rates at the reach scale may affect long-term monitoring data and any subsequent management decisions that might rely upon those data. Stream scale (population) injury estimates would typically be more important from a conservation and stewardship perspective. Electrofishing injury rates, as calculated with our models, decreased as spatial scale increased.

In the upper Yakima River basin, wild steelhead are very rare, while wild resident rainbow trout populations are relatively healthy. Wild steelhead juveniles are not visually distinguishable from resident rainbow trout before the smolt stage, which typically occurs before the fish reaches about 250 mm in length (Peven et al. 1994). Therefore, to minimize our sampling effects on the critically low steelhead population, we must have a very low effect on all *O. mykiss* less than about 250 mm in length.

Based on this study, injury due to our routine sampling on the small size-group of *O. mykiss* is low. In tributaries, 5.1% of the individuals we captured in this size-group were injured as a result of electrofishing. After accounting for multiple passes and capture probabilities, estimates of electrofishing injury rates within 100-m-long index reaches in tributaries was 4.9% annually. The stream scale electrofishing injury effect on smaller *O. mykiss* in the Yakima River was also very low (0.1%). The electrofishing injury rate among larger rainbow trout was much higher than it was for smaller fish, and resulted in an estimated annual stream scale injury of 2.1%. However, when we accounted for the proportions of all *O. mykiss* in Yakima River index sections that were above and below the 250 mm FL size, we predicted an overall stream scale injury rate for all *O. mykiss* of 0.9%. Even if we assume all of the larger rainbow trout that were injured (2.1% at the stream scale) died each year, it would still be only about one-thirtieth of the average estimated annual mortality rate for these fish in that river reach between 1991 and 1995 (61.5% average annual mortality; WDFW, unpublished data). Electrofishing injury studies that have examined delayed mortality have typically concluded that even in cases where injury rates were high (upwards of 50%), short-term delayed mortality rates have been low (McMichael 1993; Habera et al. 1996) or have not significantly affected long-term survival (Dalbey et al. 1996). Even though injury rates were very low at the stream or population scale, effects of injuries on larger rainbow trout within index reaches needs to be considered when designing long-term monitoring programs. Cumulative electrofishing injury rates could be relatively high for longer-lived and larger salmonids in sites that are sampled multiple times during the fish's lifespan and in tributaries where a high proportion of the fish present are captured. For example, large, long-lived rainbow trout living within an index reach that is sampled annually have an increasing probability of being injured by electrofishing as their size increases and the number of years they are exposed to electrofishing increases. In situations where the injury rate of these older and larger individuals is high, annual mortality is low, and the fraction of habitat sampled is large, it may be advisable to limit sampling to every other year to decrease the potential for electrofishing injuries to affect response data (e.g., growth) for research or management studies.

It is desirable to determine the cumulative effects (over multiple years) of electrofishing injuries so that total electrofishing effects can be evaluated. Determining cumulative electrofishing injury rates in annually sampled reaches is complex. Without a great amount of data, many assumptions must be made. To calculate cumulative injury rates, one would ideally have age-specific injury rates and annual survival rates and population estimates. Accounting for the multiple years that fish within a tributary index reach might be exposed to electrofishing (3 years) and for annual mortality of all fish (assumed to be 60% annual mortality after reaching age 1), we calculated the cumulative electrofishing injury rate within the reach to be 10.2% (in comparison to 4.9% injury in 1 year). Extrapolated to the stream scale, cumulative injury rate in tributaries was 0.1%, which was the same as the annual injury rate at that scale because only 1.1% of the habitat is sampled. In the Yakima River where *O. mykiss* live longer and attain a larger size, the potential for higher cumulative impacts resulting from annual sampling increases if annual mortality is relatively low. However, in situations where annual mortality is high, the cumulative impacts would not increase much over the annual injury rates because injured fish (and uninjured fish) survival is low between sampling years (i.e., injuries do not accumulate in the population if annual survival is low).

In tributaries, where we captured high proportions of the fish present, the estimated injury rate within index reaches (4.9%) was similar to the injury rate at the sample scale (5.1%). The potential to affect large populations of smaller fish or migratory fish that spend a year or less in the index area is much lower due to the lower injury rates for small-sized fish, combined with the shorter residence within the index reaches. Juvenile spring chinook salmon, for example, are relatively small when they are shocked and spend only 1 year rearing in freshwater. Frequency of using electrofishing to sample these populations of smaller fish with shorter residence times need not be restricted to less than once per year.

Although juvenile spring chinook salmon in this study were relatively resistant to electrofishing injury (perhaps due to their small size), they appeared to be more susceptible to mortality from other handling stresses, such as crowding and oxygen depletion in the holding vessel (Strange et al. 1978), than the *O. mykiss* we captured. Biologists must be aware of effects of collection and handling stress on fish that are sampled. Lower fish densities in holding vessels, combined with supplemental air or regular water changes, may do more to reduce sampling impact on fish like juvenile spring chinook salmon than reducing electrofishing injury rates.

Field sampling that involves electrofishing a large fraction of the available habitat and uses injurious electrofishing methods has the potential to injure a relatively large portion of the population being sampled. For example, if a hypothetical wild resident rainbow trout population were restricted to a 10-km reach of stream, and samplers used mark–recapture methods (two runs) to electrofish 80% of the habitat in that reach with a capture probability of 25% and injured 25% of the fish they captured, then the stream-scale electrofishing injury resulting from such an effort would be 10% ($2 \times 0.8 \times 0.25 \times 0.25$). Depending on the managers' and the public's valuation of the resource, the relationship between injury and survival, the need for the data, and the frequency of sampling, a 10% injury rate at the stream scale may or may not be acceptable.

All area-based expansions of the individual injury data assume that we captured all fish that were injured. It is possible that some injured fish are not netted and went undetected by the sampling personnel. In such a case, our estimates of individual injury rates, as well as their subsequent area-based estimates, would underestimate actual injury rates. The degree to which this may happen would be affected by environmental variables, such as turbidity, water velocity, water depth, and habitat complexity. Without the use of lethal sampling, such as sodium cyanide poisoning following electrofishing, the true injury rate in fish not captured is difficult to determine in natural streams. Collecting fish from an electrofished area by using a noninjurious method, such as seining, may be helpful in some reaches, but one would have to assume that injured fish were not more likely to be captured than uninjured fish. We did not attempt to estimate injury in fish that were exposed to electrofishing but not captured, but we believe that it is generally less than for captured fish because fish that are not captured seldom experience the galvanonarcosis and tetany commonly observed in close proximity to the anode. Other assumptions made in tributary injury rate calculations were (1) that additional exposures do not increase the sample scale injury, (2) that capture probability is the same on all electrofishing passes, and (3) that fish were equally distributed along the length of the stream. If the first two assumptions were violated, it would have increased the projected rate minimally at the reach scale due to the high percentage of fish that are captured in small tributary multiple-removal estimates. If the third assumption were violated, the relative densities between the sampled reach and the stream influence the direction of the bias. If the density of fish in the sampled reach was high relative to the rest of the stream, then the projected stream scale injury rate would be underestimated. Conversely, if fish density were higher outside the sampled reach, the injury rate estimate would be too high.

The control–treatment experimental design we used provided a baseline context for the electrofishing injuries. Had we examined only fish captured by electrofishing (i.e., no controls), our estimates of electrofishing injury rates would have been substantially higher in three of our seven experimental groups. Minor injuries were observed in some of the control fish we captured by angling. Hollender and Carline (1994) observed similar incidence of injuries (7%) in brook trout *Salvelinus fontinalis* they captured by angling. Other researchers have also noted spinal abnormalities in salmonids that they concluded were not the result of electrofishing (McCrimmon and Bidgood 1965; Gill and Fisk 1966).

We inadvertently collected control fish that were significantly larger than treatment fish in five of seven experimental groups. This size disparity, though small, could have caused us to underestimate injury at the sample scale (and the subsequent reach and stream scales) for some experimental groups. The effects of this would be most apparent at the sample and reach scales in tributaries due to the large portion of fish in those areas that are exposed to electrofishing.

The dorsoventral and lateral X rays, combined with follow-up necropsies, provided a good system for detecting injuries around the spinal column. In addition, this combination allowed us to make what we felt were accurate determinations on whether an injury was caused by our capture. If we had used only one X-ray view we would have underestimated injury rates. The lateral view provided the best injury detection. The majority of the injuries (53.7%) were detected on lateral-view plates only. Dorsoventral plates alone showed 13% of the injuries, and 33.3% of the injuries were seen on both views. We may have missed some hemorrhages because we only necropsied fish that looked irregular on the X rays. If we did miss some hemorrhages, this would have caused us to underestimate injury.

We focused our attention on two highly valued salmonid species that are commonly associated with other fish species that may also be injured as a result of our electrofishing. Although effects on the two species we examined were low at the stream scale, injury rates in nontarget species were not evaluated. We observed some mountain whitefish *Prosopium williamsoni* bleeding from the opercula following exposure to electrofishing in the Yakima River. We recommend that future electrofishing injury research take a community perspective to truly evaluate electrofishing impacts to ecosystems.

Electrofishing injury rates on the fish we examined in the upper Yakima River basin appeared to be small relative to natural annual mortality rates at the stream scale and moderate at the index reach scale. A variety of biological and sampling design considerations must be balanced against the need for the data when establishing research or monitoring efforts that use electrofishing. Even though individual fish, especially larger rainbow trout, were injured at relatively high rates by electrofishing, the combination of high annual mortality and the low percentage of the total population that is captured by electrofishing minimizes the effect of injury on the population and our monitoring data.

Acknowledgments

We are grateful for the help of Ron Martin, who was instrumental in developing the techniques used throughout the X-ray portion of the study. Bill Hopley, Michael Canino, Steven Martin, and Vernon Bogar assisted in the collection of control samples. Kenneth Ham provided much appreciated coaching on mathematical maneuvers and reviewed drafts of the manuscript. James Reynolds, Patrick Kokovsky, and Dan Schill provided constructive review comments that greatly improved the paper. This study was funded by the Bonneville Power Administration through a contract to the

Washington Department of Fish and Wildlife's Yakima Species Interactions Studies.

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Received September 22, 1997
Accepted April 15, 1998