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FINAL REPORT

INFLUENCE OF A WEAK FIELD OF PULSED DC ELECTRICITY ON THE BEHAVIOR AND INCIDENCE OF INJURY IN ADULT STEELHEAD AND PACIFIC LAMPREY

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Predation by pinnipeds, such as California sea lions *Zalophus californianus*, Pacific harbor seals *Phoca vitulina,* and Stellar sea lions *Eumetopias jubatus* on adult Pacific salmon *Oncorhynchus spp* in the lower Columbia River has become a serious concern for fishery managers trying to conserve and restore runs of threatened and endangered fish. As a result, Smith-Root, Incorporated (SRI; Vancouver, Washington), manufacturers of electrofishing and closely-related equipment, proposed a project to evaluate the potential of an electrical barrier to deter marine mammals and reduce the amount of predation on adult salmonids (SRI 2007). The objectives of their work were to develop, deploy, and evaluate a passive, integrated sonar and electric barrier that would selectively inhibit the upstream movements of marine mammals and reduce predation, but would not injure pinnipeds or impact anadromous fish migrations. However, before such a device could be deployed in the field, concerns by regional fishery managers about the potential effects of such a device on the migratory behavior of Pacific salmon, steelhead *O. mykiss*, Pacific lampreys *Entoshpenus tridentata*, and white sturgeon *Acipenser transmontanus,* needed to be addressed. In this report, we describe the results of laboratory research designed to evaluate the effects of prototype electric barriers on adult steelhead and Pacific lampreys.

The effects of electricity on fish have been widely studied and include injury or death (e.g., Sharber and Carothers 1988; Dwyer et al. 2001; Snyder 2003), physiological dysfunction (e.g., Schreck et al. 1976; Mesa and Schreck 1989), and altered behavior (Mesa and Schreck 1989). Much of this work was done to investigate the effects of electrofishing on fish in the wild. Because electrofishing operations would always use more severe electrical settings than those proposed for the pinniped barrier, results from these studies are probably not relevant to the work proposed by SRI. Field electrofishing operations typically use high voltage and amperage settings and a variety of waveforms, pulse widths (PW), and pulse frequencies (PF), depending on conditions and target species. For example, when backpack electrofishing for trout in a small stream, one might use settings such as 500 V pulsed DC, a PW of 1 ms, and a PF of 60 Hz. In contrast, the electrical barrier proposed by SRI will produce electrical conditions significantly lower than those used in electrofishing, particularly for PW and PF (e.g., PW ranging from 300 – 1,000 μs and PF from 2 – 3 Hz). Further, voltage gradients (in V/cm) are predicted to be lower in the electric barrier than those produced during typical electrofishing. Although the relatively weak, pulsed DC electric fields to be produced by the barrier may be effective at deterring pinnipeds, little, if anything, is known about the effects of such low intensity electrical fields on fish behavior.

For this research, we evaluated the effects of weak, pulsed DC electric currents on the behavior of adult steelhead and Pacific lamprey and the incidence of injury in steelhead only. In a series of laboratory experiments, we: (1) documented the rate of passage of fish over miniature, prototype electric barriers when they were on and off; (2) determined some electric thresholds beyond which fish would not pass over the barrier; and (3) assessed the incidence and severity of injury in steelhead exposed to relatively severe electrical conditions. The results of this study should be useful for making decisions about whether to install electrical barriers in the lower Columbia River, or elsewhere, to reduce predation on upstream migrating salmonids and other fishes by marine pinnipeds.

Methods

Steelhead

Study site and fish collection.—Experiments with steelhead were conducted at the Cowlitz Trout Hatchery (Washington), which was built by Tacoma Power and is operated by the Washington Department of Fish and Wildlife. Hatchery-origin adult summer steelhead were collected from a trap at Mayfield Dam on the Cowlitz River and transported to an adult holding pond at the hatchery. The concrete holding pond was about 45-m-long and 3-m-wide and received flow through hatchery water at a rate of 25 L/s. The steelhead were collected from mid-June through late July 2008 and all fish were in good condition and had no external signs of injury or disease before testing.

Experimental apparatus.—We conducted our tests in a second adult holding pond that had dimensions identical to those described above. An electric array, designed by SRI, was positioned with its upper edge 10-m from the upstream end of the pond and was 8-m-long and spanned the width of the pond (Figure 1). The array was comprised of a PVC frame with five evenly spaced pieces of rebar extending perpendicular to the length of the pond over an insulated tarp that lined the bottom and sides to prevent any electrical conductance to the concrete. The rebar served as electrodes with only the two pieces adjacent to the center actually energized. The center and outer most electrodes were parasitic and helped to maintain the electric field within the boundaries of the tarp. The electrodes were parallel to each other, spaced 1.25-m apart, and water depth in the pond was 0.6 m. For all the electrical conditions we tested, personnel from SRI mapped the voltage gradients within the volume of water energized by the array (Figure 2).

A series of customized Programmable Output Waveform (POW) pulsators, supplied by SRI, converted incoming alternating current to pulsed direct current (PDC) and served as the power supply for the electrode array. The output of the pulsators was controlled and monitored with a computer and software provided by SRI. An external, remote on-off switch connected to the computer system allowed observers to start and stop the electric output as needed. Heavy gauge insulated wire was used to connect the pulsators to the array and we reduced trip and electrical hazards by enclosing wires in electrical conduit.

Steelhead passage through the electric barrier.—To evaluate the passage of steelhead through the barrier, we exposed groups of fish to one of four voltage gradients (0.6, 0.8, 0.9, or 1.1 V/cm) at a PW of 0.4 ms and a PF of 2 Hz (Table 1). These voltage gradients were typical values measured near the water surface in the trough between the energized electrodes (Figure 2) and, for convenience only, we named our treatments after them. Control fish were exposed to the un-energized barrier only. For our first tests, we assigned 30 fish each to the treatment and control groups and exposed them to electrical conditions analogous to those known to deter sea lions in laboratory tests (i.e., 0.6 V/cm, 0.4 ms PW, and 2 Hz; Zeligs and Burger 2009). For subsequent tests, we only used fifteen fish per group.

To start a test, three fish were netted from the holding pond, transferred to the experimental pond, and contained at the downstream end with a fence for 10 minutes. Fish were released by removing the fence and allowed to swim volitionally upstream to the array. As the fence was raised, we energized the array with the appropriate test conditions and turned on video cameras to record the behavior of fish as they approached and passed over the array. Upstream of the array, we placed a large tarp over the water in an area with subsurface inflow to provide incentive for fish to pass through the barrier. Due to the reluctance of some steelhead to swim volitionally to the upstream end of the pond, all fish were slowly crowded to within 3-m of the array. Fish were given 5 min from the time of release to cross the array before the test was ended. Control fish were subjected to the same procedures except that no electrical power was applied to the array. Treatment and control groups were alternated throughout the day to account for changing light and temperature conditions. After each test, the steelhead were transferred to another pond and monitored for mortality for at least 72 h. Differences in the proportion of fish in each group that successfully passed over the array were compared using a chi-squared test (α=0.05).

Electrical threshold testing.—We subjected groups of six fish to various electrical conditions to determine levels that would prevent most fish from passing through the barrier (Table 1). We primarily changed PW and PF and used the same procedures as described above. These tests were simple, "range finding" procedures meant to provide insight into the influence of PW and PF on fish behavior. We report the number and percentage of fish in each group that successfully passed over the array.

Injury tests.—To assess the potential of spinal or other injury to steelhead that might be near the electrodes when they pass over the array, we exposed 10 fish to 1.9 V/cm, 0.4ms PW, and 2 Hz. Another group of 10 fish served as controls and received no electricity. For each test, one steelhead was moved to the experimental pond, gently crowded toward the array, and confined over the array with gates positioned on each side. After fish had settled near the center of the array, we started our video cameras and energized the electrodes for 10 s. For control fish, we simply counted off 10 s. After the test, the upstream gate was removed and fish were guided to the end of the raceway, gently corralled and netted, placed into a lethal dose (300 mg/L) of buffered tricane methanesulfate (MS-222), and taken to a processing station.

We measured each fish for length (mm) and weight (g), removed a blood sample from the caudal vein using ammonium heparinized Vacutainers, tagged the fish, and placed them singly in plastic bags. Fish were then frozen completely before transport to our laboratory. On 21 August, fish were taken to Skyline Hospital in White Salmon, WA, and radiographed laterally and dorsally. Radiographs were reviewed by two biologists to note any dislocations or fractures of the vertebral column. Later, fish were thawed, filleted on both sides to expose the axial skeleton, inspected for hemorrhages, and photographed. Hemorrhages were rated by worst apparent severity based on the scale devised by Reynolds (1996). Differences in the mean severity of apparent injury between control and treatment groups were tested for significance using a two-tailed *t*-test (α=0.05).

Assessment of the soft start technology.—We conducted some rudimentary, qualitative tests of the soft start technology to be used in any field-based versions of the electric barrier. Basically, this technology allows electrical conditions within the array to slowly ramp up before coming to full power, perhaps providing fish with time to exit the array. To assess the influence of soft start technology on fish behavior, we followed the procedures described above for injury testing. However, the electrodes were energized with a 5 s soft start. Fish behavior was recorded by overhead cameras and noted by an observer for 30 s. Ten fish were tested and we report qualitative information on their behavioral responses.

Pacific lamprey

Fish collection and maintenance.—Upstream migrating, adult Pacific lamprey were collected (*N* = 78) from the Willamette Falls Dam fishway near Portland, OR, on 30 June 2008 during a scheduled dewatering operation. Fish were collected by hand, transferred to an insulated tank with aerated water, and transported back to our laboratory. Equal numbers of fish were maintained in four 1.5-m-diameter circular tanks with aerated water from the Little White Salmon River at 15°C. All lampreys were in good condition with no external signs of injury or disease before being tested.

Experimental apparatus.—Tests were conducted in a straight-sided annular tank (4-m-long, 0.4-m-wide, and 0.5-m-deep; Figure 3). Flow through the tank was maintained at 0.1 m/s by use of a recirculating pump and river water (15°C with a conductivity of 36 µS) was added at a rate of 10L/min. The electric array was comprised of four flat metal electrodes spaced 0.5-m apart along one straight edge of the tank. The array was controlled with a single POW pulsator, with the two center electrodes energized and the outer electrodes parasitic. Personnel from SRI mapped the voltage gradients within the volume of water energized by the array (Figure 4). Lighting was set up to simulate a natural photoperiod during the day and four 25-watt red lights were suspended above the tank to provide some ambient light for filming at night.

Lamprey passage over the electric barrier.—Groups of lampreys (*N* = 24) were assigned to three treatment groups, each with a different suite of electrical conditions (Table 2). For each test, three fish were netted from a holding tank, placed in the test tank, and allowed a period of adjustment from 1500 to 2300 h. From 2300 to 0200 h, we recorded the number of times any lamprey passed over the unenergized array by means of a low-light overhead camera and digital video recorder. This was our control period and we filmed lamprey movements for the first 30 minutes of each hour. We defined a passage event as a fish moving over all four electrodes in either direction. At 0200 h, we energized the electrodes with the appropriate test conditions and filmed the same group of fish until 0500 h. For each suite of electrical conditions, we repeated the test eight times (using new fish each time) and compared the mean passage rates between control and treatment periods with a paired *t*-test (α=0.05).

Results

Steelhead

There was no significant difference in the percentage of steelhead that passed over the array when it was off (100%) compared to when it was energized with 270 V, had a surface voltage gradient of 0.6 V/cm, 0.4 ms PW, and 2 Hz (98%; Figure 5). Typically, fish swam slowly over the array near the bottom and close to the raceway wall within the adjacent shadow. Increasing the surface voltage gradient to a range of 0.8 – 1.1 V/cm reduced the passage success of steelhead over the array by 13 – 33%, values that were not significantly lower than control fish for each individual test (Figure 5). When the data from these trials were combined, however, the proportion of fish that passed over the array when it was energized was significantly lower than the value for control fish (Chi-square = 7.79, df = 1, P = 0.0053).

At a surface voltage gradient of 0.6 V/cm (300 V pulsed DC), a 12.5 to 50-fold increase in PW along with a unit increase in PW altered the behavior of steelhead and prevented several fish from passing over the array (Table 3). The percentage of fish that failed to pass over the array ranged from 33 – 100%, with more fish refusing to pass at higher pulse widths. Typically, fish would swim into the array, encounter the electrical field near the first parasitic electrode, and turn away and move downstream.

There were no significant differences in severity or frequency of apparent injuries (i.e., hemorrhages) between control fish and those exposed to 850 V, a surface voltage gradient of 1.9 V/cm, 0.4 ms PW, and 2 Hz (Figure 6). Mild to moderate hematomas were common in both groups, particularly near the caudal peduncle, indicating possible handling effects. All spinal radiographs of these fish were negative.

There were no discernable differences in the behavioral response of steelhead to the electrical array with the soft start technology. However, it was difficult to expose fish to consistent treatment conditions because some swam continuously over the array or held immediately downstream of the array. Of three fish that were stationary and positioned over the array when the soft start was initiated, none appeared to respond to the electricity until after 5 s had passed.

Pacific lampreys

The mean passage rate of lampreys during control and treatment periods did not differ significantly when fish were exposed to either 0.6 or 1.35 V/cm at the surface (applied voltages of 97 and 191 V), 0.4 ms PW, and 2 Hz (Figure 7). During these experiments, fish typically moved up and downstream and showed normal anguilliform swimming and searching behavior. When the voltage gradient and pulse rate were increased to 1.8 V/cm and 5 ms, the mean passage rate of lampreys over the array declined by 80% (Figure 7). Fish encountering the electrical field would often turn away (and sometimes or never return) or rapidly sprint or burst-swim through the area. On one occasion, a fish entered the electric field, got near the energized electrodes, rolled over on its side, and showed rigid, involuntary, "twitchy" swimming. This behavior persisted until the fish slowly moved away from the strongest electric fields, toward the parasitic electrodes. Like steelhead, a 12.5 to 50-fold increase in PW along with a unit increase in PF elicited 2 to 10-fold decreases in the mean passage rate of lampreys over the array (Table 2).

Discussion

Based on our results and those of others, the notion of a weak field, pulsed DC electric barrier that can deter the movements of pinnipeds yet not impact the migrations of anadromous fish, has merit. Recently, Zeligs and Burger (2009) showed that captive California sea lions would not pass through a weak field electric barrier, even when food was present. Work with other pinnipeds has also reported similar findings (Cave 2007a, b). In contrast, our results indicate that adult steelhead and Pacific lampreys will pass through small, weak field electric barriers under a variety of conditions. Further, steelhead exposed to a relatively high voltage gradient (1.8 V/cm) but low intensity PW and PF had the same level of apparent injuries as unexposed, but handled, control fish. Although our results provide some initial insight into the behavioral responses of fish that may encounter a low intensity electric barrier in the field, more work is needed. Questions remain, for example, about extending results from laboratory experiments to conditions in the field, including our use of hatchery fish and miniature, prototype arrays, and the relevance of the electrical conditions experienced by our fish. Given the potential size and electric field characteristics of a barrier proposed for installation below Bonneville Dam on the Columbia River (Mike Holliman, SRI, personal communication), a complete understanding of fish behavior in response to the barrier may be tenable only after careful *in-situ* testing of a full-scale apparatus.

The electrical conditions we exposed our fish to were unique and lower than those used for typical electrofishing operations and electrical barriers designed to block fish migrations (e.g, Swink 1999). As such, we did not expect to see reactions such as galvanotaxis or narcosis when fish experienced our weak electric fields. We assumed that fish would sense the electric field, but did not know how or whether they would react. In our tests, both species of fish passed readily through electric fields with a voltage gradient at the surface similar to levels targeted by SRI for deterring pinnipeds in the field. When we increased surface voltage gradients to range of 0.8 – 1.1 V/cm, the passage rate of steelhead declined, and when we exposed lampreys to 1.8 V/cm (at a PW of 5 ms), their passage rate declined by 80%. Recent modeling simulations of the hypothesized voltage gradients within a barrier placed in the Columbia River indicate that the electrical field is not homogenous and fish could encounter the voltage gradients we exposed them to in the laboratory. Within a barrier placed in the field (and in our tests; see Figure 2), voltage gradients would vary vertically—from near the substrate (high) to the surface (low)—and horizontally, from the outside of the array (low) to the center (high). What fish will do when they encounter such heterogeneous, and probably large, electrical fields in the wild is unknown and cannot be predicted unequivocally from the results of our tests. We discuss reasons for this below.

Although we showed that increasing the PW, and to a lesser extent, the PF, led to significant reductions in passage of fish over the laboratory barriers, high levels of these variables are thought to be unnecessary in a barrier designed to deter pinnipeds. This is because the sensitivity of pinnipeds to electrical fields is much higher than that of fish (Zeligs and Burger 2009). Our intent with these experiments was to test the limits of the electrical systems we were using and create conditions that would unequivocally stop fish. Because high PW and PF are often used in electric barriers designed to block fish movements, we were not surprised that our tests resulted in similar effects. For example, a pulsed-DC electrical barrier set to a 2-ms PW and a PF of 10 Hz completely blocked the spawning migration of sea lampreys *Petromyzon marinus* on the Jordan River, Michigan (Swink 1999). Also, electric barriers installed in the Central Arizona Project canal were set to a PW of 25 ms and a PF of 2 Hz (Clarkson 2004). Further, high PF's are often used in electrofishing because of their effectiveness in eliciting galvanotaxis (but they also contribute to injury in fish; see below). Thus, avoiding high PW and PF seems prerequisite to an electrical barrier destined for installation in the Columbia River and, as far as we know, this is the intent of designs being proposed by SRI. However, because the responses of wild, hungry pinnipeds to a low intensity electrical barrier in the field are unknown, and because of the possibility that wild pinnipeds may learn to tolerate or become habituated to the barrier, it may be necessary to increase slightly the settings on the barrier. We showed that a PW as low as 5 ms and an increase in PF from 2 to 3 Hz contributed to reductions in passage success of steelhead and Pacific lampreys. Based on discussions with SRI, it seems unlikely that PF would increase much above 2 – 3 Hz in a field-based barrier, but it is conceivable that PW up to 2 – 3 ms might be needed. We recommend further testing of fish passage at PW ranging from 0.75 to about 3 ms in combination with small increases in PF.

Exposing steelhead to 850 V, 1.9 V/cm, 0.4 ms PW, and 2 Hz resulted in no significant injuries beyond those attributable to handling alone. Although this was a relatively high voltage gradient that might even stun fish during electrofishing in waters of low conductivity (Reynolds 1996), we suspect that the low PW and PF contributed to the lack of response and serious injury in our fish. Indeed, high PW (or high duty cycles—the ratio of voltage "on" time to total time within one cycle; see Reynolds 1996) and high PF are thought to be the factors most responsible for serious injury to fish during electrofishing (Reynolds 1996). For example, high levels of PF (50 – 60 Hz) coupled with duty cycles ranging from 25 – 50% increased the incidence of spinal injury in large rainbow trout relative to other waveforms (Sharber and Carothers 1988; Holmes et al. 1990). Because, as we discussed earlier, the electrical barrier proposed for deterrence of pinnipeds will not use high levels of PW or PF, we surmise that serious injury to migrating adult salmonids swimming through such a barrier would be rare or non-existent. We do not know whether adult Pacific lampreys—or other fishes—would be seriously injured if exposed to the electrical conditions within a field-based array because we did not test this. Because of their benthic nature, future work should include an assessment of injuries in adult lampreys exposed to electrical conditions that might occur near the electrodes of a barrier slated for installation in the field.

There are several reasons why we cannot use our results to predict unequivocally the outcome of fish encountering and trying to pass through a low intensity electric barrier in the field. First, the electrical conditions fish were exposed to in our laboratory tests may not be the same as those fish would encounter in the field. As of this writing, the design and electric field characteristics of a barrier to be installed in the Columbia River are hypothetical and under development by SRI. The electrical conditions experienced by fish in the field will depend on the electrical field itself, the depth of migration (fish closer to the electrodes will experience more severe voltage gradients), fish size, and perhaps other unknown factors. As we mentioned above, recent modeling simulations by SRI suggest that the electrical conditions we exposed our fish to will, at the least, be within the range of those predicted to occur within a barrier placed in the Columbia River. Second, the size of an electric barrier in the field will be quite large—recent estimates by SRI suggest the barrier could be 40-m-long, as wide as the river (i.e., a few hundred meters), and would energize a volume of water from the bottom to the surface. In our tests, fish had to pass over arrays that were about six (steelhead) or 2.5-m-long (lampreys). Such differences in scale make it difficult to predict how fish will react when they encounter such a large volume of electrified water in the field. Third, our tests were done with the electrical barrier always on, which represents a worst-case scenario for fish in the wild but is different from how SRI proposes to operate the device. If an electric barrier were deployed in the field, SRI states that it would only be energized if pinnipeds were in the near vicinity. Such intermittent operation of the device could influence fish passage or behavior, depending on the location of fish within the array when it becomes energized. Finally, the motivation of fish in the wild to migrate upstream could influence their propensity to swim through a weak field electric barrier. Although we hypothesize that such motivation should facilitate passage through a barrier in the field, our laboratory tests could not address this factor. In the end, the potential large size of a barrier in the field with its large volume of energized water, coupled with nuances in fish behavior, make it clear that laboratory experimentation can only take our understanding so far.

Predation by pinnipeds on upstream migrating salmonids and other fishes in the lower Columbia River represents a conflict between species listed under the Endangered Species Act and a quandary for fish and wildlife managers. To alleviate some of this problem, serious consideration is being given to the installation of a very large, weak field electrical barrier just downstream from Bonneville Dam that would: (1) deter pinnipeds from entering tailrace areas, where fish congregate and are presumably easy to catch; and (2) not impede the passage of or injure fish in any way. Although SRI plans to incorporate many design elements in the barrier to address these two points (e.g., low PW and PF, intermittent operation, “shielded” electrodes), the efficacy of such a device depends on many factors. From the pinniped viewpoint, there are several things to consider. First, it is unknown whether the results from studies using captive, trained animals are applicable to animals and conditions in the wild. Specifically, we do not know how wild pinnipeds will react to an electrical barrier in the field, or whether they will learn to avoid or tolerate it. Finally, even if the barrier prevents pinnipeds from entering tailrace areas, we do not know if the predatory impact of these animals will just "shift" to other areas. This is a complicated issue and depends in part on whether tailrace areas near dams contribute to a higher capture success and predation rate by pinnipeds relative to other areas. If this is true, then blocking pinnipeds from these areas could reduce predation. If not, the overall impact of predation by pinnipeds on salmonids might not change. We have already discussed many of the factors that will determine the efficacy of a low intensity electrical barrier on fish performance and injury. In the end, only limited knowledge and insight of the potential efficacy of this device can be gained through laboratory experimentation. Our work, and that of Ostrand et al. (2009), represents a good start, and perhaps more should be done in the laboratory (e.g., testing mild to moderate increases in PW and PF). Nevertheless, to understand truly the potential effectiveness and impact of a low intensity electrical barrier will require installation and testing in the field. The underlying complexities and issues surrounding this device are too important and vague to rely on laboratory experimentation alone.

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Table 1. Summary of experimental conditions for tests of the effects of weak pulsed DC fields on adult steelhead at the Cowlitz Trout Hatchery. *N* is the sample size.

		Electrical parameters			
Date	Experiment Type	Voltage gradient (V/cm)	Pulse Width (ms)	Frequency (Hz)	*N*
7/16-7/17	Passage behavior	0.6	0.4	2	30
		0	0.4	2	30
8/4-8/5		0.8	0.4	2	15
		0.9	0.4	2	15
		1.1	0.4	2	15
		0	0.4	2	15
7/18	Threshold	0.7	5	2	6
		0.7	10	2	6
		0.7	10	3	6
		0.7	20	2	6
		0.7	20	3	6
8/6-8/7	Injury	1.9	0.4	2	10
		0	0.4	2	10
8/7	Soft start	1.9	0.4	2	10

Table 2. Summary of experimental conditions for tests of the effects of weak pulsed DC fields on adult Pacific lamprey at the Columbia River Research Laboratory.

	Electrical parameters			
Group	Voltage gradient (V/cm)	Pulse Width (ms)	Frequency (Hz)	*N*
1	0.6	0.4	2	24
2	1.35	0.4	2	24
3	1.8	5	2	21

Table 3. Steelhead passage over an electrical array with a surface voltage gradient of 0.6 V/cm and varying combinations of pulse width and frequency at the Cowlitz Trout Hatchery. *N* is the number of fish released.

Electrical parameters				
Pulse Width (ms)	Frequency (Hz)	*N*	Passed	Percent passed
5	2	6	4	67%
10	2	6	4	67%
10	3	6	0	0%
20	2	6	2	33%
20	3	6	1	17%

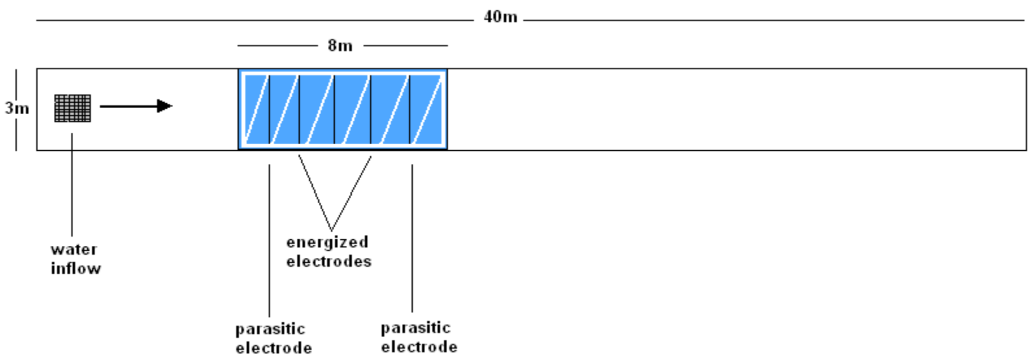

Figure 1.—Overhead schematic of the experimental pond and electrical array at the Cowlitz Trout Hatchery.

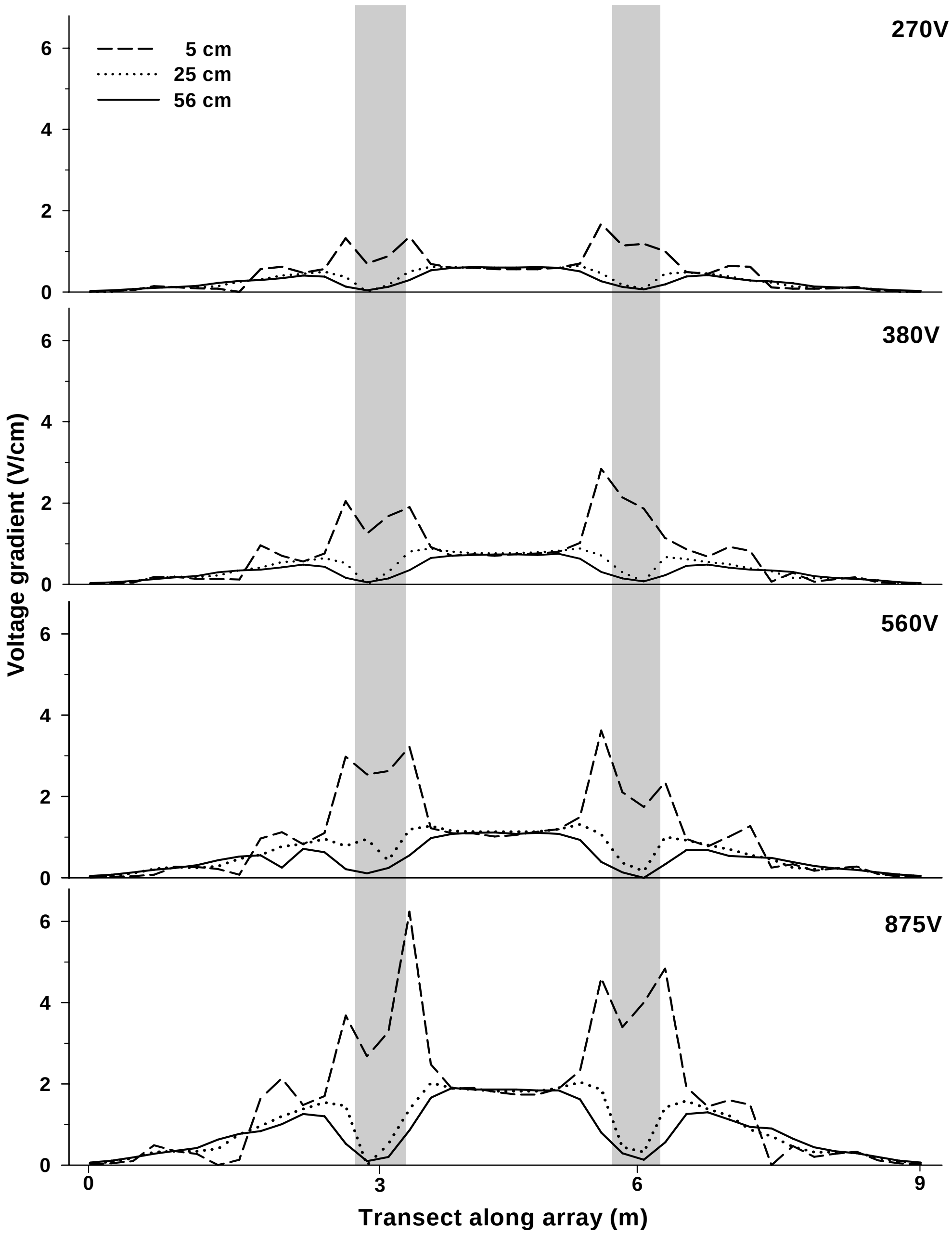

Figure 2.—Voltage gradient maps of the electric array at the Cowlitz Trout Hatchery for different applied voltages and depths measured from bottom. Gray bars represent energized electrodes.

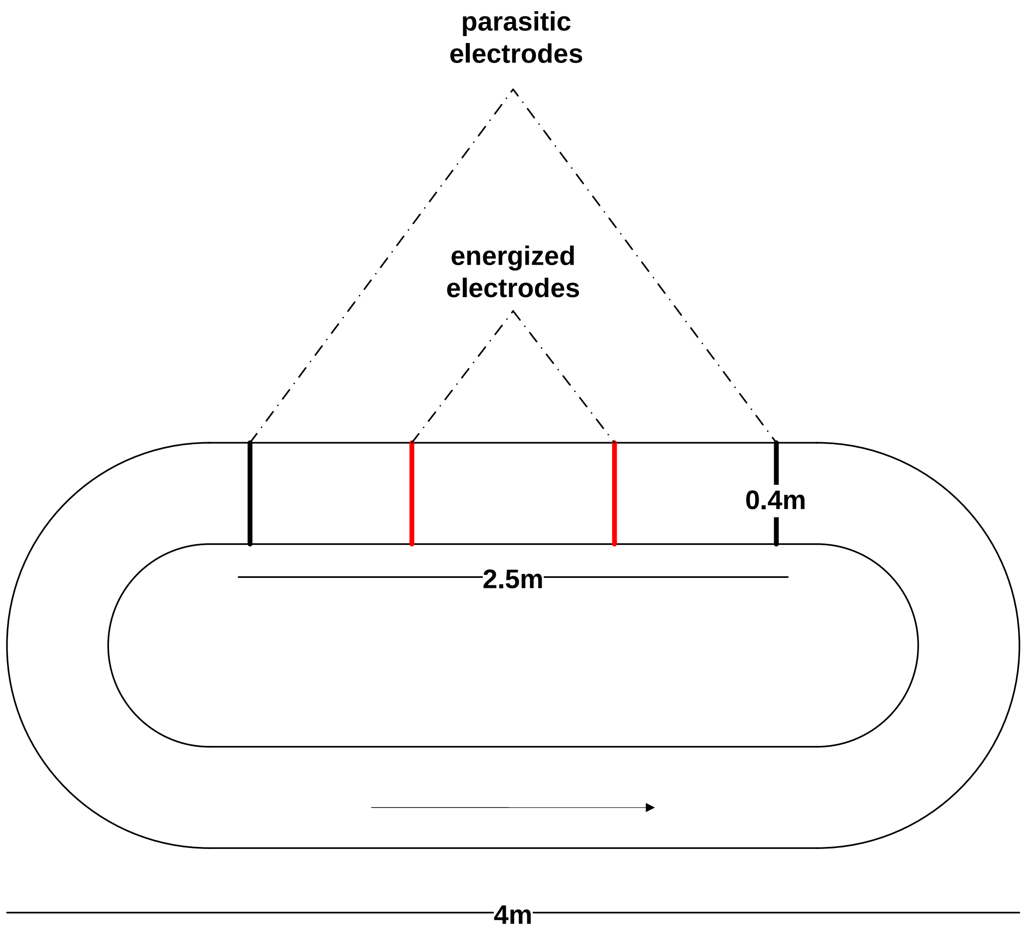

Figure 3.—Overhead schematic of an annular tank with a electric array used for lamprey passage studies at the Columbia River Research Laboratory, Cook, WA. Arrow denotes direction of water flow.

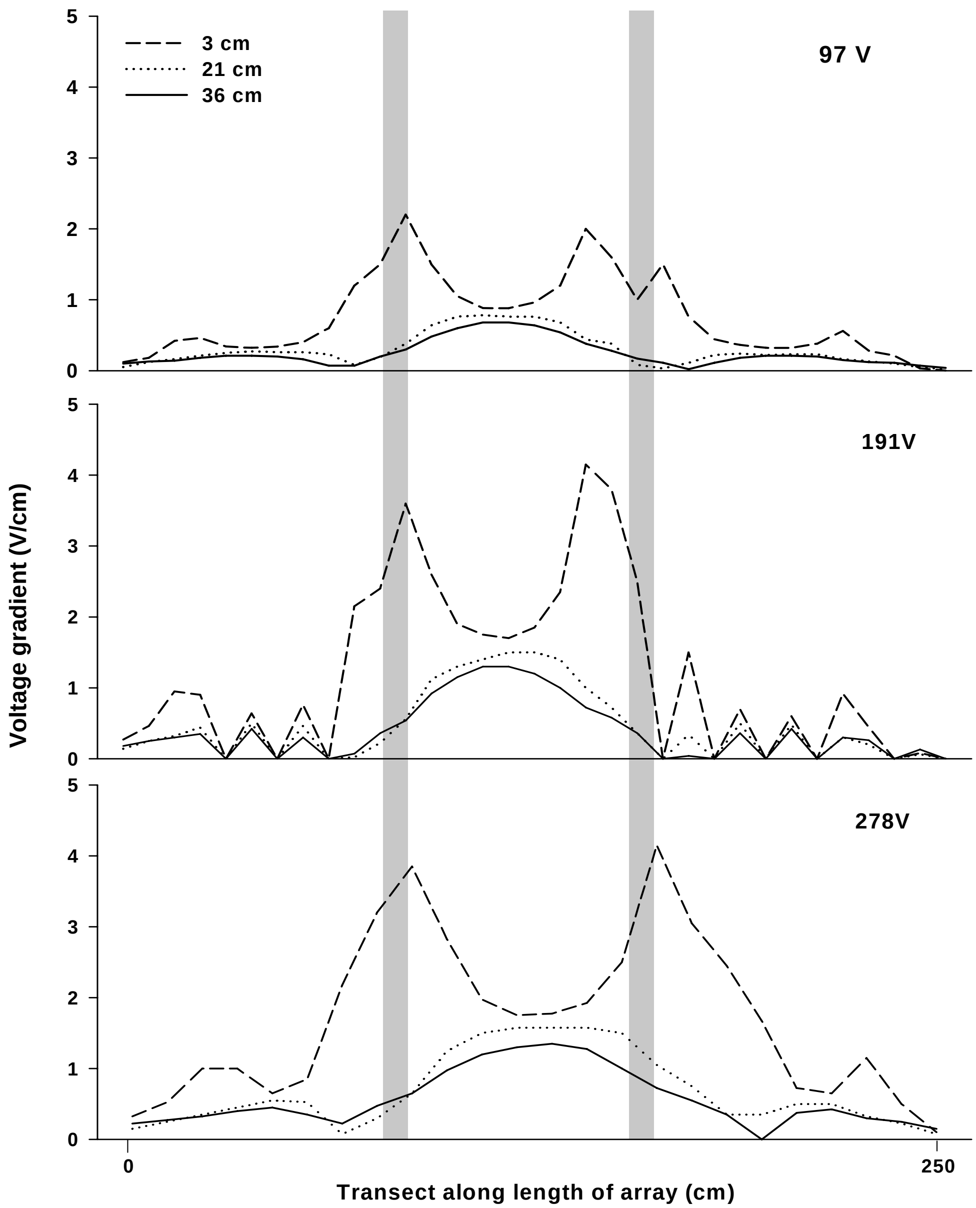

Figure 4.—Voltage gradient maps of the electric array at the Colombia River Research Laboratory for different applied voltages and depths measure from bottom. Gray bars represent energized electrodes.

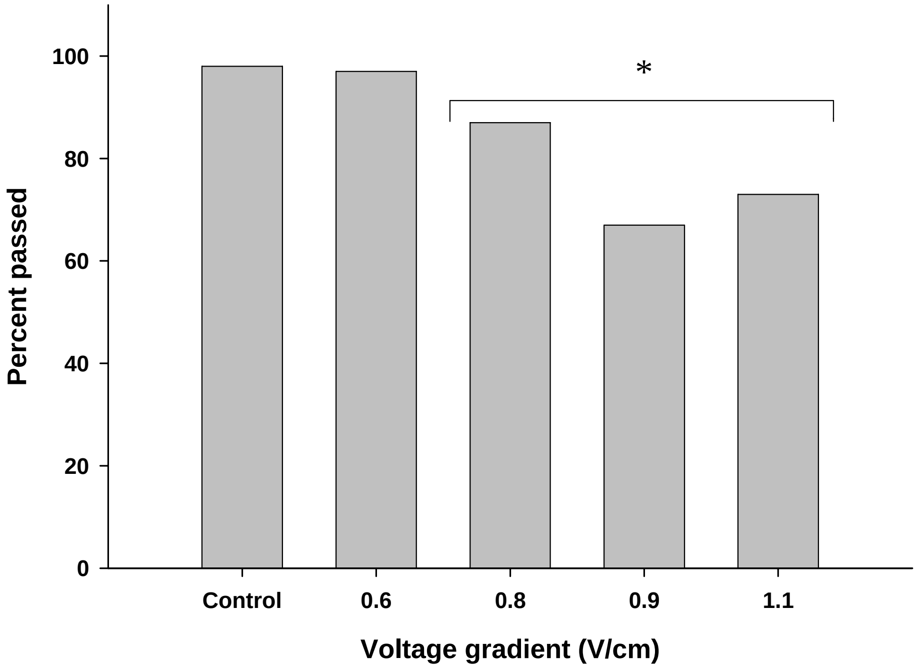

Figure 5.—Percent of adult steelhead that passed over an energized electrical array at different surface voltage gradients. The asterisk denotes that the mean passage rate of the pooled samples was significantly ($P < 0.05$) lower than control fish. Sample size for each bar ranged from 15-30 fish.

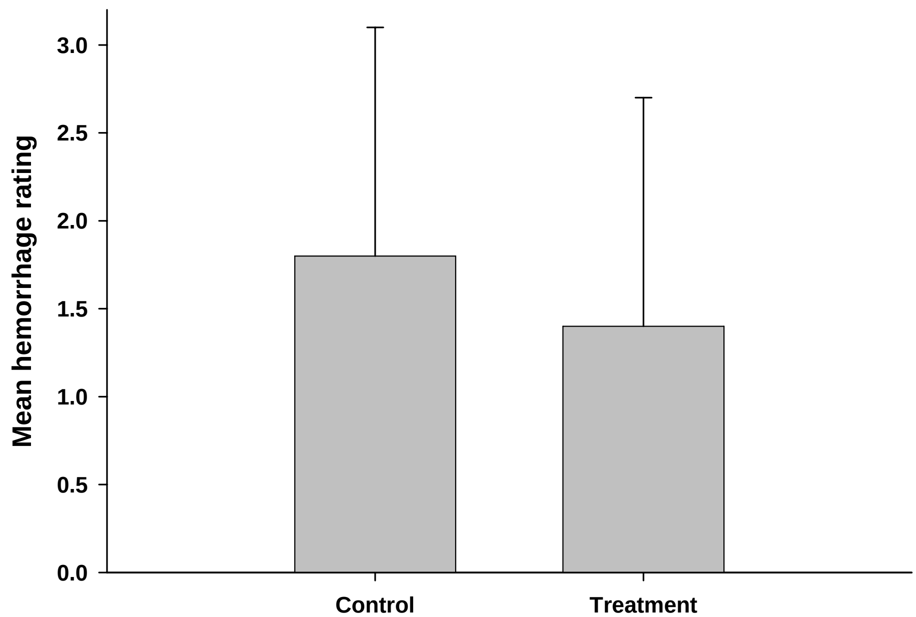

Figure 6.—Mean (and SD) hemorrhage rating of adult steelhead subjected to 10-s of 1.1 V/cm, 0.4 ms pulse width, and a pulse frequency of 2 Hz and then handled compared to fish that were just handled (control). Sample size for each bar was 10 fish.

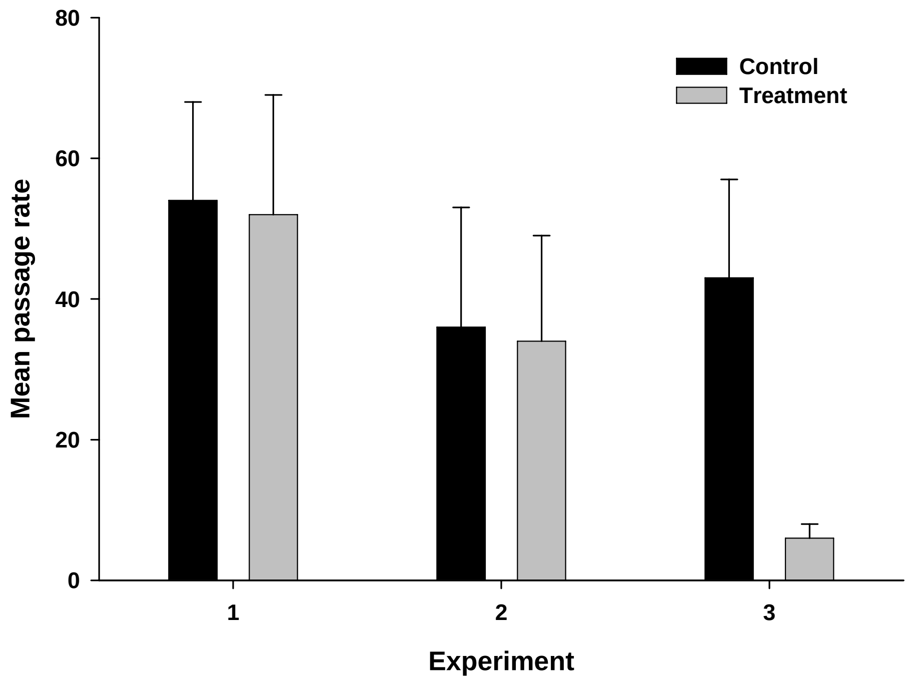

Figure 7.—Mean (and SD) passage rate of lampreys through an electric barrier when off (control) and energized (treatment). Experiment 1 had a voltage gradient of 0.6 V/cm, a pulse width of 0.4 ms, and a pulse frequency of 2 Hz. Experiment 2 had 1.35 V/cm, 0.4 ms, and 2 Hz, and experiment 3 had 1.8 V/cm, 5 ms, and 2 Hz. Sample size for each bar ranged from 21-24 fish.