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Effectiveness of Electrical Fish Barriers Associated with the Central Arizona Project

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Abstract.—The Central Arizona Project (CAP) canal delivers Colorado River water into the Gila River basin. During its planning and construction, issues arose regarding the unwanted entrainment and transport of nonindigenous fishes and other aquatic biota into, through, and out of the canal. One control strategy was the emplacement of electrical fish barriers on two CAP distributary canals to prevent fishes from moving upstream into the Gila River drainage. The operation, maintenance, and effectiveness of these barriers are described for the period 1988–2000. Documented outages totaled more than 100 h, representing less than 0.001% downtime since installation. It is nearly certain that outages allowed immigration by undesired fish(es). Immigrations that occurred when the barriers were operating according to design criteria indicate that the barriers do not totally block the passage of upstream-migrating fish. The proximate sources of electrical barrier outage included component damage from lightning strikes, component breakdowns, failure to adhere to component maintenance and replacement schedules, failure to incorporate adequate protection and redundancies to certain system components, inadequate training of personnel, and unknown causes. Known outages of remote monitoring systems (which are necessary to document outages and understand the potential for undocumented barrier outages) totaled more than 400 d, representing about 3% of the period of barrier operations. The complexity of electrical barrier systems and the problems such intricacy creates for operation and monitoring may always preclude absolute effectiveness. Additional refinements to system components, personnel training, and operation procedures may reduce barrier failures but add further to that complexity. Management agencies will have to determine the cost-effectiveness of such refinements.

The use of electric fields to prevent upstream movements of fish was initially applied in North America to control efforts for sea lamprey *Petromyzon marinus* in Great Lakes tributaries in the 1950s (Applegate et al. 1952; Erkkila et al. 1956; McLain 1957; McLain et al. 1965). The goal of that program was to reduce sea lamprey depredation on declining stocks of lake trout *Salvelinus namaycush* and other prey by blocking lamprey spawning migrations in tributaries to the Great Lakes. Electrical barriers were installed on streams considered inappropriate for low-head dams that served a similar function. The electrical barrier program was only partially successful, and was largely replaced in 1960 when the application of a selective lampricide (3-trifluoromethyl-4-nitrophenol [TFM]) gained widespread use (McLain et al. 1965).

With further technological development of pulsed-DC electrical barrier systems in the 1980s, limited use of electrical barriers in sea lamprey control efforts has been revived as part of an expanded integrated pest management system (Katopodis et al. 1994; Swink 1999). Electrical barriers have also been applied to solve other fish control problems, including escapement estimation (Palmisano and Burger 1988) and prevention of entrainment (Burrows 1957; Barwick and Miller 1998). Information on much of these uses is largely hidden among gray literature reports, and mostly relates to the effectiveness of barriers on short-term fish control (i.e., little is available on long-term system reliability).

During the planning and construction of the Central Arizona Project (CAP), a 540-km aqueduct that delivers Colorado River water to the Gila River basin, issues arose regarding the unwanted entrainment and transport of nonindigenous fishes and other aquatic biota into, through, and out of the canal. The concern was that these organisms could negatively affect native species and established, nonnative sport fisheries. It was deemed technically and economically infeasible to keep organisms from entering and leaving the CAP; instead, a control strategy was chosen to prevent them from moving upstream in the Gila River drainage once outside the CAP (USFWS 1994, 2001). Where site-specific circumstances warranted (direct connections between CAP waters and the Gila River drainage and insufficient availabil-

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TABLE 1.—Status and trends of fish species native to the Gila River drainage, Arizona, New Mexico, and Sonora, Mexico. Wild status designations are as follows: D = declining, E = extirpated from the basin, Ex = extinct, I = increasing. Legal status designations are as follows: S = state-protected, PE = proposed endangered, E = endangered, T = threatened.

Native species	Status: Wild	Status: Legal
Roundtail chub *Gila robusta*	D	S[a]
Headwater chub *G. nigra*	D	
Gila chub, *G. intermedia*	D	PE
Bonytail *G. elegans*[b]	E	E
Colorado pikeminnow *Ptychocheilus lucius*[c]	E	E
Loach minnow *Rhinichthys cobitis*	D	T
Speckled dace *R. osculus*	D	
Longfin dace *Agosia chrysogaster*	D	
Spikedace *Meda fulgida*	D	T
Woundfin *Plagopterus argentissimus*	E	E
Desert sucker *Catostomus clarki*	D	
Sonora sucker *C. insignis*	D	
Flannelmouth sucker *C. latipinnis*	E	
Razorback sucker *Xyrauchen texanus*[bc]	E	E
Desert pupfish *Cyprinodon macularius*	E	E
Santa Cruz pupfish *Cyprinodon arcuatus*	Ex	
Gila topminnow *Poeciliopsis occidentalis*	D	E
Apache trout *Oncorhynchus apache*[a]	I	T
Gila trout *O. gilae*	I	E
Striped mullet *Mugil cephalus*	D	

[a] Designated a sport fish by the Arizona Game and Fish Department.
[b] Hatchery stocks are present in the basin.
[c] Repatriated, nonreproducing stocks are present in the basin.

ity of gradient to install low-head barriers), electrical fish barriers were constructed to prevent such movements.

The operation, maintenance, and effectiveness of electrical fish barriers in preventing upstream movements of fishes in central Arizona canal systems during 1988–2001 are described in this study. The history of documented electrical barrier outages at these sites is reported, as is the history of major outages of the electrical barrier remote monitoring systems. The latter data are necessary to understand the potential for undocumented outages. The development of standard operating procedures (SOP) that detail outage response scenarios for the electrical barrier systems are also briefly described. Information on the long-term effectiveness of such technological solutions to biological problems are needed to understand the complexity of electrical barrier systems, assess their utility for future applications, and refine current operations.

Study Sites

The Gila River basin of Arizona, New Mexico, and Sonora, Mexico, historically supported 20 native fish species (Table 1). At present, one species is recently extinct, seven are endangered, another is proposed endangered, three are threatened, and the remaining have suffered significant declines in abundance and distribution. Five species have been extirpated from the basin.

Established introductions of fishes to the basin, primarily to provide sport or as bait to support sport fisheries, have led to such fishes greatly outnumbering native taxa (Table 2). Nonnative fishes are extant in most waters of the basin, where they tend to dominate or have completely displaced the native ichthyofauna. The CAP canal is exclusively occupied by nonindigenous fishes, and only two to four native species remain in other study area canals and tributary rivers below their regulating dams. The major impacts of nonnative fishes on natives include predation, competition, hybridization, and parasite and disease transmission (Moyle et al. 1986).

Electrical barriers were constructed in 1988 on two Salt River Project canals (Figure 1a). The barriers were intended to prevent fish movements from the CAP into the Salt and Verde river systems upstream. At the electrical barrier sites, the Arizona Canal is 18.5 m wide, and the South Canal is 15.8 m wide. The maximum depth in both canals is approximately 2.5 m in these areas. Both are concrete lined and steep sided. Recent annual flow volumes over the electrical barriers were near 7.24

TABLE 2.—Status and trends of fish species introduced to the Gila River drainage, Arizona, New Mexico, and Sonora, Mexico. Distribution (Distr) status designations are as follows: W = widespread, L = localized, R = rare. Trend status designations are as follows: S = stable, E = expanding range, R = recently introduced, trend uncertain.

Introduced species	Status	
	Distr	Trend
Fathead minnow *Pimephales promelas*	W	E
Goldfish *Carassius auratus*	L	S
Grass carp *Ctenopharyngodon idella*	L	S
Common carp *Cyprinus carpio*	W	E
Red shiner *Cyprinella lutrensis*	W	E
Bigmouth buffalo *Ictiobus cyprinellus*	L	S
Black buffalo *I. niger*	R	
Smallmouth buffalo *I. bubalus*	R	
Largemouth bass *Micropterus salmoides*	W	S
Smallmouth bass *M. dolomieu*	W	E
Bluegill, *Lepomis macrochirus*	W	E
Redear sunfish *L. microlophus*	W	S
Green sunfish *L. cyanellus*	W	E
Black crappie *Pomoxis nigromaculatus*	W	S
White crappie *P. annularis*	L	S
Black bullhead *Ameiurus melas*	W	E
Yellow bullhead *A. natalis*	W	E
Flathead catfish *Pylodictis olivaris*	W	E
Channel catfish *Ictalurus punctatus*	W	E
Western mosquitofish *Gambusia affinis*	W	E
Sailfin molly *Poecilia latipinna*	L	S
Guppy *Poecilia reticulata*	L	S
Walleye *Sander vitreus*[a]	L	S
Yellow perch *Perca flavescens*	R	
Threadfin shad *Dorosoma petenense*	W	S
African cichlids *Tilapia* spp.	L	E
Yellow bass *Morone mississippiensis*	L	S
Striped bass *M. saxatilis*	L	E
White bass *M. chrysops*	L	E
Northern pike *Esox lucius*	L	R
Arctic grayling *Thymallus arcticus*[b]	L	S
Rainbow trout *Oncorhynchus mykiss*[b]	W	S
Brown trout *Salmo trutta*	W	S
Brook trout *Salvelinus fontinalis*	W	S

[a] Formerly *Stizostedion vitreum*.
[b] Routinely stocked.

$\times$ 10^8 m^3 (587,000 acre-ft) and 4.93 $\times$ 10^8 m^3 (400,000 acre-ft) for the Arizona and South canals, respectively, with maximum rates near 34.0 m^3/s (1,200 ft^3/s).

Another electrical barrier was installed in 1990 on the San Carlos Irrigation Project Pima Lateral Canal (Figure 1b). This barrier was to prevent CAP fishes from entering the Florence-Casa Grande Canal and moving upstream to the Gila River, the San Pedro River, and Aravaipa Creek (which is inhabited by federally threatened native fishes). The concrete-lined Pima Lateral Canal is 24.5 km downstream from the Florence-Casa Grande Canal diversion on the Gila River, and transports approximately 1.65 $\times$ 10^8 m^3 (134,000 acre-ft) per annum at a maximum rate of 18.7 m^3/s (660 ft^3/s). Soon after the electrical barrier on the Pima Lateral Canal was constructed, additional interconnects between the CAP and the Florence-Casa Grande Canal were built, rendering the barrier ineffective. Thus another barrier was placed in 1990 on the Florence-Casa Grande Canal 4.2 km downstream from the Gila River (Figure 1b). The Florence-Casa Grande Canal is unlined and carries approximately 3.79 $\times$ 10^8 m^3 (307,000 acre-ft) per annum at a maximum rate of 35.8 m^3/s (1,265 ft^3/s). Canal dimensions vary from 15 to 30 m wide, with an average depth of 1 m. As the barrier on the Pima Lateral Canal was considered redundant, operations ceased in 1992.

Methods

Electrical barrier design.—Electrical fish barriers were designed by Smith-Root, Inc., and incorporate seven major elements: (1) direct current pulse generators, (2) electrodes on weir structures,

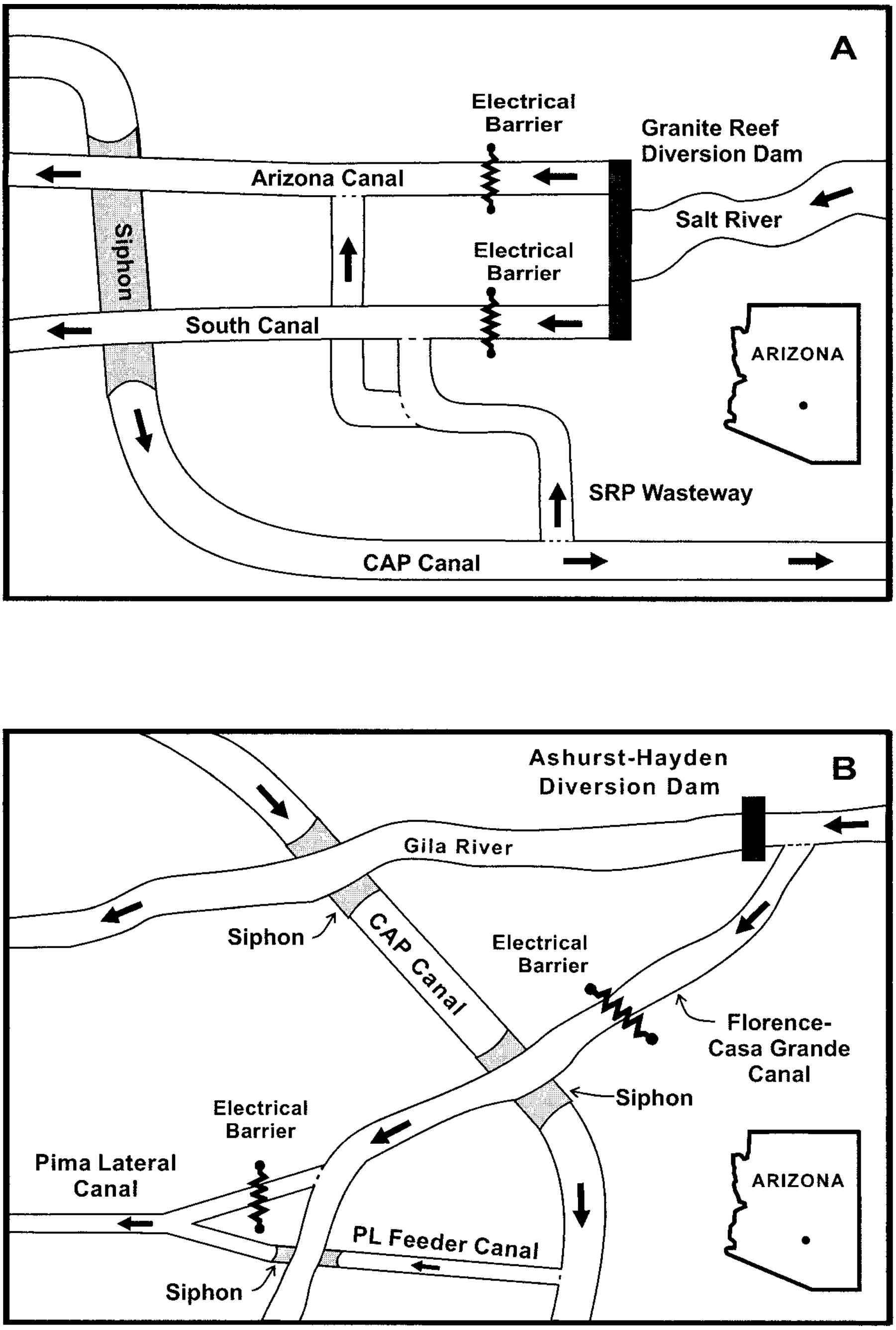

FIGURE 1.—Diagrams of the interconnections between the Central Arizona Project (CAP) and the **(A)** Salt River Project and **(B)** San Carlos Irrigation Project canals, showing relationships with surface waters and locations of electrical fish barriers; PL denotes Pima Lateral.

(3) electrical cables connecting pulse generators and electrodes, (4) emergency backup generators, (5) weirs across the bottoms of canals to hold electrodes, (6) electronic remote monitoring of barrier conditions and alarm status, and (7) SOP manuals developed specifically for each system that detail contingency actions during barrier failures or component outages.

Six pulse generators produce power for each barrier, and electrodes transmit the electric field to the water. Pulse generators are connected in a series to create a constant-strength electrical field across the length of the weir. The strength of the electric field within each fish barrier is designed to be maintained at a minimum of 1.0 V/cm at the water surface; the strength increases with proximity to the electrodes. The pulse width is 25 ms at 2 pulses/s, although the system is adjustable to between 8 and 32 ms duration at 1–13 pulses/s. The barriers are powered by 240-V, 75-kilovolt–ampere single-phase power transformers (SRI 1990).

In the event of a power failure, an automatic transfer switch starts a 50-kilovolt–ampere backup power generator (SRI 1990). There is an 8-s delay following a primary outage until the slave transfer to the auxiliary generator is switched, another 3-s delay for the slave transfer, and a 5-s auxiliary generator start-up. Thus, there is a 16-s interruption of power to the barrier following a primary power outage until backup power commences.

A junction box distributes AC power and trigger pulses for the six pulse generators. The pulsator unit plugged into channel 1 of the junction box becomes the master, which controls the timing to synchronously trigger the remaining slave pulsators. If the master channel fails, a master-to-slave switch-over causes the pulsator plugged into channel 2 to assume the role of the master pulse generator (SRI 1990).

Electric field lines are purported to extend evenly from the bottom to the top of the water surface (SRI 1990) and to run parallel to flow (i.e., fish attempting to swim upstream are oriented head-to-tail along the maximum voltage gradient). Although the physiological mechanism of reaction is controversial (see Sharber and Sharber-Black 1999), the major responses of fish in electrical fields (reviewed by Snyder 1992) include reactive detection, inhibited or undirected motion, taxis (automatism), narcosis (petit mal seizure), and partial or full tetanus (grand mal seizure). These responses are generally ordered as the fish experience increasing field intensities toward the anode. As fish swim upstream toward the electrified weir at an electrical barrier, they theoretically either swim away when entering the reactive detection zone, or continue upstream until other responses overwhelm their ability to orient in the water current, resulting in drifting or swimming downstream away from the electrical field.

Redundancy in the pulsators allows for the failure of one or more of them without compromising the entire barrier as well as the immediate replacement of a faulty pulse generator without disrupting the barrier (SRI 1990). Two additional pulse generators are stored on-site at each barrier location for this purpose.

Weir structures were installed in canal bottoms to serve three functions: (1) as a platform for electrode installation, (2) to assure a uniform water depth to improve barrier efficiency, and (3) to increase the water velocity over the barrier by reducing the depth (to make upstream fish movement more difficult). Weirs are composed of high silica content concrete that insulates the electrodes. At maximum flows in each canal, water depth over the weirs is approximately 1.2 m (SRI 1990).

The electrodes in the Salt River Project canals are high-carbon steel railroad rails. The electrodes installed in the Florence-Casa Grande and Pima Lateral canals were 2.5-cm diameter stainless steel rods, but the lower five electrodes at the Florence-Casa Grande Canal were replaced with railroad rails in 1999. The seven electrodes at each barrier are evenly spaced at 1-m intervals, and the voltages from the six pulse generators are applied between successive pairs of electrodes.

The Salt River Project and San Carlos Irrigation Project barriers were fitted with automated monitoring alarm systems in January 1992. Except during communication outages, these systems continuously monitor barriers for certain abnormal conditions, and feature automatic detection and selection of either voice or computer-to-computer data connections (SRI 1991). When the system detects an alarm condition, it calls one or more preprogrammed phone numbers at various intervals until the alarm is acknowledged. In addition to reporting the status of the six pulse generator outputs, the status of several additional conditions were monitored (e.g., main power and auxiliary power). The system also initiates weekly reports that are phoned to Smith-Root, Inc.

Standard operating procedures manuals were not original components of barrier designs but were added in response to management agency concerns about contingency actions should the barriers or their components fail. These manuals detail potential component or barrier failure scenarios, and define the specific remedial actions to be undertaken to return the barriers to a fully operational (and redundant) state.

Monitoring records.—Smith-Root, Inc., conducted quarterly site inspections to monitor the operation and condition of the barrier systems and their components. Monitoring consisted of the following measurements: (1) voltages through the electrode arrays, (2) in situ electrical field strengths, (3) water conductivity, (4) pulse generator output levels, (5) remote alarm conditions, (6) auxiliary generator crank tests, and (7) various ''routine'' inspections (e.g., generator battery water levels and generator fuel and oil levels). Smith-Root, Inc., generated and distributed quarterly reports summarizing these data that form the basis of a portion of the information presented here.

Beginning in 1992, Smith-Root, Inc., initiated weekly cellular phone communications with each site and downloaded alarm histories. These histories included the status of the pulse generators, auxiliary generators, AC power, power to remote monitoring systems, and certain other component and site conditions.

In addition to the communications Smith-Root, Inc., initiated with the barriers, remote monitoring systems phoned reports to Smith-Root, Inc., whenever alarm conditions warranted. Histories of both monitoring reports were compiled by Smith-Root, Inc., and distributed with brief summary reports of the status of each electrical barrier at monthly or quarterly intervals. In the last quarter of 1999, the Salt River Project took over the barrier remote monitoring and reporting of the Salt River Project canals to the U.S. Bureau of Reclamation. Although Smith-Root, Inc., and the Salt River Project remote monitoring systems are separate, the types of information monitored by each system are similar. Smith-Root, Inc., continued their monitoring and reporting tasks at the San Carlos Irrigation Project site. These remote monitoring reports form a large basis of the information summarized herein, but it was impossible to confirm outage durations provided by Smith-Root, Inc., from these data.

Finally, when unusual events at electrical barriers warranted, correspondence among Smith-Root, Inc., the Salt River Project, the San Carlos Irrigation Project, and the U.S. Bureau of Reclamation that discussed barrier operations, maintenance, and monitoring also provided important information for this report, as did site visits by the author.

Annual fish monitoring was initiated in the CAP, in canal reaches above and below electrical barriers, and in river reaches upstream of canal diversions beginning in 1991. Monitoring was conducted during periods of minimum water deliveries (CAP) or during river and canal ''outages,'' where upstream dam releases were ceased or greatly reduced to facilitate upstream reservoir retention and downstream canal maintenance. Sampling gears included boat and backpack electroshockers, seines, minnow traps, trot lines, angling, and dip, hoop, gill, and trammel nets. No attempts at marking fish below the electrical barriers were made.

Results

Barrier Operations and Effectiveness

Electrical fish barriers on South and Arizona canals went online in November 1988, and remote monitoring of barrier operations began in January 1992. Operational histories prior to 1992 were based solely on periodic maintenance inspection reports (i.e., there were no continuously monitored data), and no outages during that period were reported by Smith-Root, Inc.

The electrical fish barrier on the Pima Lateral Canal was constructed in late 1989 and went online prior to the first delivery of CAP water down the Pima Lateral Feeder Canal in April 1990. The electrical barrier on the Florence-Casa Grande Canal was constructed February–April 1990 and went online in May 1990. Prior to the January 1992 installation of the remote monitoring systems, barrier effectiveness was determined by physical inspections and preventative maintenance of barrier components.

The first documented barrier outage occurred on the Pima Lateral Canal on 2 June 1990, when it was disabled for a period of 12–36 h following the unauthorized disconnection of primary power to the barrier; the auxiliary power generator operated until it ran out of fuel (Table 3). The lack of a timely response by maintenance personnel allowed the outage to continue for this extended period of time. There were no other reported or suspected outages of the Pima Lateral Canal electrical barrier during its period of operation (i.e., electrical outages were handled routinely through backup generators), and the barrier purportedly remained operational according to design specifications.

The next documented electrical barrier failure occurred 23 December 1993 on the Arizona Canal following loss of primary power and failure of the battery that powered the backup generator (Table 3). This outage lasted 2 h 16 min. Although backup generator batteries at all electrical barrier sites were equipped with continuous trickle charging systems, apparently in this case the battery lost its capability to hold a charge. A policy was subsequently instituted to exercise batteries monthly (and later weekly) using backup generators, and

TABLE 3.—Known outages of electrical fish barriers on Salt River Project and San Carlos Irrigation Project canals, 1988–2000. There were no outages prior to January 1990 based on site maintenance inspections performed by Smith-Root, Inc.; history since January 1990 is based on remote monitoring records provided by Smith-Root, Inc., and the Salt River Project. Abbreviations are as follows: PL = Pima Lateral Canal; SO = South Canal; AZ = Arizona Canal; FCG = Florence-Casa Grande Canal.

Date	Site	Duration	Cause	Remedy
2 Jun 1990	PL	12–36 h	Backup generator out of fuel	Monthly inspection of fuel levels
31 Mar 1992	SO	15 min	Barrier and/or remote monitoring failure; cause undetermined	Not documented
23 Dec 1993	AZ	2 h 16 min	Backup generator battery failure	Generator exercised monthly to charge battery; battery replaced every 2 years
2 Sep 1994	SO	2 d	Lightning strike damage to several pulsators (possible outage)	Repaired pulsators
14 Sep 1995	AZ	4 h	Backup generator ran out of fuel	Backup generator fuel tank refilled
25 Jan 1996	FCG	1 h 15 min	Backup generator fuel supply turned off	Fuel supply turned back on
23 Aug 1996	FCG	2 min	Generator start-up problems	Not documented
2 Sep 1997	FCG	2 min	Backup generator failure	Not documented
8 Sep 1997	FCG	14 min	‘‘Fuel interruption’’ to backup generator	Not documented
12 Sep 1997	FCG	6 min	Backup generator failure	Not documented
28 Aug 1998	FCG	1 h	Backup generator controller ‘‘over-run’’ errors	Not documented
4 Sep 1998	FCG	1 h 30 min	Backup generator controller ‘‘over-run’’ errors	Not documented
23 Sep 1998	FCG	1 h 20 min	Backup generator controller ‘‘over-run’’ errors	Replaced governor
23 Jul 1999	AZ	1 h 42 min	Lightning strike damage to electrical components	Component replacement
14 Sep 1999	SO	Undetermined	Lightning strike damage to pulsators	Not documented
20 Nov 1999	SO	Undetermined	Failure to activate barrier prior to rewatering of canal	Proposed standard operating procedure modifications

batteries routinely were to be replaced at 2-year intervals (see below). The Salt River Project has since added remote monitoring of auxiliary generator battery voltages.

The consequences of this outage were soon apparent, as several grass carp (a nonnative species stocked by the Salt River Project downstream of the electrical barriers for weed control but not previously found above) were captured above the barrier during subsequent fish monitoring. No fish species have yet been found below the electrical barrier on the Florence-Casa Grande Canal that do not also occur upstream.

A suspected barrier outage on the South Canal on 2 September 1994 was apparently caused by a lightning strike that damaged several pulse generators (Table 3). As the barriers are designed to be effective with less than their full complement of pulsators operational, it is uncertain how ‘‘fish tight’’ the barrier remained during this 2-d component failure. Smith-Root, Inc., reported the barrier ‘‘mostly operational’’ during this period.

At least nine additional documented electrical barrier outages resulting from failures of the backup generators to power barriers following primary power disruptions occurred between 1995 and 1998, all but one occurring at the Florence-Casa Grande Canal facility (Table 3). These lasted between 2 min and 4 h, and were attributed to either undetermined causes (4), human error (1), insufficient fuel supply (1), or generator controller ‘‘overrun’’ errors (3). With the exception of the fuel supply problem (which was later ameliorated by addition of remote fuel supply monitoring), no remedies for these types of outages are personally known to have been proposed.

On 23 July 1999, pulse generators 1, 4, and 6 on the Arizona Canal failed for 1 h 42 min due to a suspected lightning strike, which also damaged the switchboard and prevented pulser unit 2 from taking over as the master pulse generator. Thus the barrier was not functional during this period (Table 3). Lightning apparently caused similar damage to the South Canal electrical barrier pulse generators 3, 5, and 6 on 14 September 1999. As other pulsators remained operational during this 2 h 10 min component failure, Smith-Root, Inc., considered

TABLE 4.—Outage history of remote monitoring systems of electrical fish barriers on Salt River Project and San Carlos Irrigation Project canals, 1990–2000. Only outages that lasted more than 24 h are reported; scores of shorter outages resulting from unique events or intermittent problems are not listed. See Table 3 for abbreviations.

Date	Site	Duration	Cause	Remedy
11 May 1992	FCG	2 d	Bad modem chip	Modem chip replaced
22 Aug 1994	FCG	8 d	Memory corrupted	Restored settings
2 Feb 1995	FCG	13 d	Loose cable connection	Cable connection repaired
7 Aug 1995	AZ	4 d	Defective CPU and modem cards	Replaced CPU and modem cards
11 Sep 1995	SO	59 d	Cellular damage from lightning strike[a]	Installed new antenna, replaced cellular equipment, switched cellular service provider
3 Jan 1996	SO AZ FCG	28 d	Incompatible modem upgrade	Original modem restored; software upgraded for new modem
1 Apr 1996	FCG	<8 d	Lost settings and memory	Settings restored
19 Aug 1996	AZ SO	undetermined	Undetermined	Data were later recovered; no barrier failure noted
23 Dec 1996	FCG	undetermined (<8 d)	Undetermined	Reset the system
6 Jan 1997	FCG	21 d	Component card failure	Replaced card and other system components
29 Sep 1997	FCG	10 d	Undetermined	Not documented
8 Oct 1997	FCG	20 d	Modem module failure	Total system replacement
19 Nov 1997	FCG	28 d	Phone line problems	Not documented
22 Mar 1999	AZ	35 d	Defective cell phone	Replaced cell phone
30 Jul 1999	AZ	22 d	Cell phone turned off	Turned on cell phone
23 Sep 1999	SO	16 d	Undetermined	SRI remote monitoring ceased 30 Sep 1999
17 Oct 2000	SO AZ	29 d	Overwritten history files	Not documented

[a] Barrier outage may have occurred during monitoring outage as grass carp were captured above the electrical barrier following a period without a known barrier outage (Smith-Root, Inc., inspection report, 21 November 1995).

the barrier to be fish tight, but the event is noted here as a possible barrier outage (Table 3).

The most recently documented outage of electrical fish barriers occurred at the South Canal during the 29 November 1999 rewatering operation following a routine canal ''dry-up'' (Table 3). In this instance, the canal was partially rewatered prior to the barrier being electrified. The duration of this outage was undetermined. Better definition of canal dewatering and rewatering scenarios in SOPs has been recommended to prevent future similar occurrences.

The capture of two grass carp above the South Canal electrical barrier during annual fish monitoring on 23 October 1995 implied a prior barrier failure, but remote monitoring records did not indicate any power interruption. A 59-d cellular communications outage to the Smith-Root, Inc., remote monitoring system occurred prior to that time, but the Salt River Project's remote monitoring was functional during that period, and it did not report alarms other than routine. Smith-Root, Inc., acknowledges that some fishes are able to traverse fully operational electrical barriers during low-flow conditions. Similar captures of grass carp on 8 January 2001 in the Arizona Canal in the absence of prior known barrier outages support this theory. Salt River Project records show a several week period in 2000 when flows into the canal (and over the electrical barrier) from the Granite Reef Diversion Dam were low. A vertical steel plate 13 cm high was emplaced across the width of the weir at the Arizona Canal barrier in 2001 to present additional obstacles to fishes attempting to swim upstream during low-flow conditions. Similar devices were recently incorporated at the Florence-Casa Grande and South canal barriers.

In October 1999, I released approximately one dozen 3–4 cm-red shiners into the middle of the electrical field of the Florence-Casa Grande Canal barrier with about 15 cm of flowing water over the weir. Fish swam erratically but never tetanized, and some were able to swim upstream above the barrier.

Remote Monitoring Outages

The causes of remote monitoring outages were highly variable, ranging from simple human error to complete system failure (Table 4). The causes of several long-term outages were undetermined, as were most intermittent outages.

SOP Development

Salt River Project barriers.—The first Salt River Project SOP manual was developed in early 1990, and it described the Arizona and South Canal electrical barrier systems, their inspection procedures, and emergency operating procedures. The latter section provided timetables for specific actions to be taken in the event of any of six failure scenarios, which ranged from the failure of one or two pulse generators (the barrier remains fish tight) to complete system failure (the barrier is not effective). This SOP allowed up to 8 h of system failure prior to requiring the initiation of corrective actions.

The Salt River Project SOP was revised twice in 1991, first to include Smith-Root, Inc.'s, Electrical Barrier Operation and Maintenance Manual, maintenance checklists, notification procedures, and revised corrective actions to be taken in the event of barrier failure, and then to provide quarterly inspection reports to the U.S. Bureau of Reclamation. Barrier failure scenarios were tightened to require immediate corrective action responses by technicians.

Revision of the 1991 SOP was initiated following the discovery of two grass carp above the electrical barrier on the Arizona Canal in January 1994. Several improvements to the maintenance program were incorporated into the SOP, adding fuel level and battery voltage alarms, a personnel notification list, cranking tests for auxiliary generator batteries and door alarms to generator buildings, and tightened failure scenarios. This SOP version was finalized in 1997.

San Carlos Irrigation Project barriers.—The first SOP submitted by the San Carlos Irrigation Project for the Pima Lateral Canal and Florence-Casa Grande Canal barriers was in early 1991, which was modeled after the 1990 Salt River Project SOP. In late 1991 and early 1992, the San Carlos Irrigation Project SOP was revised to include increased inspection frequencies, the maintenance of inspection records, the addition of emergency contacts, and a provision that gates on the Ashurst-Hayden Diversion Dam to the Florence-Casa Grande Canal be shut if sufficient operating power cannot be provided to the barrier within 3 h after an initial shutdown.

Discussion

Barrier Outages

Known outages of electrical fish barriers on the Salt River Project and San Carlos Irrigation Project canals totaled more than 100 h, representing a downtime of less than 0.001% since installation. Although this proportion is small, it is nearly certain to have been sufficient to allow the immigration of undesired fish(es) based on the captures of grass carp above the Salt River Project electrical barriers. The management agencies that called for the emplacement of electrical barriers to protect existing native and sport fisheries from downstream contamination appeared to accept the likelihood that these barriers would not be 100% effective, but the barriers were designed and built to ''totally block the passage of upstream migrating fish'' (SRI 1990). Increasing economic, social, and ecological impacts of nonnative species introductions to the USA and elsewhere are reaching crisis proportions (GAO 2001). As the purpose of the electrical barriers is to prevent upstream establishment of new, nonnative species, and nonnatives have transgressed the barriers during relatively brief outage periods, the goal of 100% blockage should be pursued; anything less will not guarantee that new species invasions do not occur.

The proximate sources of electrical barrier outage included the major categories of mechanical failure and human error. Mechanical causes included component damage from lightning strikes, manufacturing flaws, and undetermined ''gremlins.'' Human errors have included the failure to adhere to component maintenance and replacement schedules, inadequate training of personnel, and failure to incorporate adequate protection and redundancies to certain system components.

Lightning was a recurring source of failure of electrical barriers in central Arizona. Grounding and lightning-arresting measures to protect system components from lightning have been incorporated at some barrier sites, but lightning damage continues to occur. Additional protection measures—such as the installation of lightning rods, surge suppressors, or other devices—likely would further reduce electrical outages and component damage. While some of these steps have been recommended by the barrier manufacturer, few have been implemented, presumably due to their high costs.

In addition to known barrier outages that ostensibly allowed breaches of the barriers by fish, it is nearly certain that at least one species (grass carp) successfully transgressed the electrical barriers on the Salt River Project canals during periods without a known history of electrical outage, based on the detection of the species above the barriers where they have never been stocked. There are no similar data for other species, but grass carp is one of only two species known from below the barriers in the Salt River Project canals that is not also resident above. The other species, striped bass, remains rare in catches from the Salt River Project canals, and it has not been recorded from above the electrical barriers (U.S. Bureau of Reclamation, unpublished data). There are no species from the Florence-Casa Grande Canal system that have similar distributions from which a barrier transgression could be easily detected.

The movements of grass carp over Salt River Project barriers without known barrier outages suggest that electrical barriers do not ''totally block the passage of upstream migrating fish,'' even when operating according to design criteria. Smith-Root, Inc.'s, explanation for such occurrences, which have been suspected at other electrical barrier facilities (D. Smith, Smith-Root, Inc., personal communication), is that during low-flow conditions (5–8 cm deep), large-bodied fishes may not absorb enough electricity to be stunned due to the reduced surface area of their bodies exposed to the electrical field. I have been unable to find documentation of this purported physiological phenomenon in the literature, but I offer no alternative hypothesis. Although not tested, the addition of low vertical obstacles across barrier weirs should, in theory, prevent future transgressions by large-bodied fishes via this avenue.

The observation that adult red shiners released into the electrical field at the Florence-Casa Grande Canal barrier failed to tetanize as expected is bothersome. The power outputs of the electrical barrier systems were designed to approximate 1 V/cm, but voltages near the center electrodes typically read 1.3–1.6 V/cm (Smith-Root, Inc., data), and voltage settings on the pulsators are maximized (B. Moorhead, Salt River Project, personal communication). Small fish seem less affected by an electric field, perhaps due to the smaller voltage gradients they experience and a smaller surface area exposed to that gradient (Reynolds 1983), but the manufacturer was surprised that red shiner did not tetanize and drift downstream when exposed to the main electrical field (D. Smith, Smith-Root, Inc., personal communication).

The 1-V/cm datum is higher than threshold values producing tetany via pulsed DC in most species studied (Sternin et al. 1976; cited by Snyder 1992), although the range of threshold data for freshwater fishes is 0.05–5.5 V/cm. Because so little information of this type is available for the many species and water quality conditions encountered in the wild, perhaps more conservative (higher) voltage outputs should be produced (although equipment development and replacement likely would be necessary). It should be noted, however, that this field ''test'' does not necessarily model how a fish approaching the electrical field from downstream would behave, only that tetany did not occur as expected. It has been a challenge to devise controlled experiments that model fish responses to electric fields in flowing waters (Hilgert 1992).

Remote Monitoring and SOP

Refinement of alarmed components and software to better monitor barrier status would also increase system reliability by helping to identify the causes of barrier failures (there were several outages of undetermined cause) and thus the means by which to remedy them. Existing refinements, such as the remote monitoring of backup generator fuel levels and routine exercising and replacement of generator batteries, have enhanced barrier reliability, but additional measures would be beneficial (e.g., the remote monitoring of backup generator battery cranking power and other backup generator functions; see Table 3).

The reliability of remote communication systems for barrier status monitoring must be improved. Known outages of the remote monitoring systems totaled more than 400 d, which represents about 3% of the period of barrier operations. Although physical inspections of barriers during or following many of these monitoring outages did not indicate that total barrier failures had occurred, it could not be determined with certainty that they did not. Modem redundancy and other solutions to this serious problem must be considered. The inventory of known and unknown causes for monitoring failures (Table 3) suggests that the entire system of remote monitoring perhaps should be reevalated. Remote monitoring data are absolutely necessary to document barrier failures and to identify outage causes.

In most cases it was not possible to verify the durations of barrier outages with alarm monitoring reports provided by the barrier manufacturer. Software upgrades that precisely identify and report which components failed, when they failed, and when each component was restored to operation should be installed. Comprehensive, independent verification of barrier operations via enhancement of automatically generated alarm reports should be required to ensure the integrity of the relationship among the barrier manufacturer, the entities responsible for their day-to-day operation and maintenance, and resource management agencies.

The development and refinement of SOP manuals appears invaluable in reducing and documenting the sources of barrier failures, and presumably further refinements will reduce future outages. Management agency review of these procedures prior to their adoption proved critical to identifying certain biological components of barrier operation procedures (e.g., how to manage fishes in a canal reach between an electrical barrier and natural surface water connections following barrier failures). A longer term review of operational data as conducted here also appears useful for refining operations, or at least for identifying recurring and potential sources of barrier component failures for managers to consider. A periodic system review where every potential source of barrier failure is contemplated, corrective or preventative solutions are identified, and then the entire process examined by independent referees might also be a worthwhile exercise.

Conclusions

The unforeseen environmental problems that inevitably arise following human alterations of natural systems often give rise, in turn, to further bioengineering efforts (Ehrenfeld 1981; Meffe 1992). Often these bioengineering ''solutions'' cascade into further applications of technology to solve problems created by their initial (and subsequent) application. In the present case, the construction of large main-stem dams to control the hydrology of the Colorado River fostered the introduction of nonnative sport fishes (and their associated biota) for recreation. The operation of the CAP to deliver Colorado River water to the interior of Arizona transports nonnative biota into the Gila River basin, where they can negatively impact the basin's native fishes and established sport fisheries. Installations of electrical fish barriers on CAP distributary canals were intended, in part, to prevent this effect.

Yet complexity of electrical barrier systems and the problems such intricacy creates for barrier operation and monitoring may always preclude their absolute effectiveness. In this instance, barrier transgression by a single pair of fish could be sufficient to render the system a failure (i.e., if a barrier is not 100% effective, it is ineffective). Additional refinements to system components, personnel training, and operation procedures have the potential to reduce occurrences of barrier failures, but add further to that complexity.

In fairness to the barrier manufacturer, their electrical barrier systems and remote monitoring capabilities have been refined and upgraded over the dozen-plus years of technological advancement since the installation of the original systems in the late 1980s. However, entities responsible for the operation and maintenance of barriers have been hesitant to shoulder such expensive component replacements. Annual operation and maintenance costs (including labor, energy, and Smith-Root, Inc., maintenance contracts) for central Arizona electrical barriers average between US$12,700 and $14,500 per barrier (B. Moorhead, Salt River Project, and A. Fisher, San Carlos Irrigation Project, personal communications). The cost estimate provided by Smith-Root, Inc., for recommended system upgrades for each barrier is approximately $100,000. Management agencies must determine whether such upgrades will be cost effective and compulsory. The estimated cost for a totally new canal barrier system is approximately $500,000, including $330,000 for construction (R. Badgett, Smith-Root, Inc., personal communication).

Given all this effort and expenditure toward ensuring fish-tight barriers, it is ironic that the agencies operating the electrical barriers will not support comprehensive management following an outage to ensure removal of fishes from canal reaches between diversions and the electrical barriers. Such actions would require cessation of water deliveries for undetermined periods of time, thereby potentially interfering with water delivery contracts. Yet without a renovation of these reaches, fishes that pass the barriers have access to upstream river systems. At present, there are only a handful of nonnative species in the CAP that are not also in Gila River basin streams, but it is likely new species will enter the canal over its expected 100-year project life.

In the final analysis, CAP electrical barriers are halfway technologies (Frazer 1992) that cannot solve the ultimate problem of omnipresence of nonnative fishes and other alien aquatic biota. However, until that ubiquity is addressed and solved, the need for electrical fish barriers remains, and we must therefore continue to struggle with improving their bioengineering.

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References

Applegate, V. C., B. R. Smith, and W. L. Nielson. 1952. Use of electricity in the control of sea lampreys: electromechanical weirs and traps and electrical barriers. U.S. Fish and Wildlife Service Special Scientific Report: Fisheries.

Barwick, D. H., and L. E. Miller. 1998. Effectiveness of an electrical barrier in blocking fish movement. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 50(1996):139–147.

Burrows, R. E. 1957. Diversion of adult salmon by an electric field. U.S. Fish and Wildlife Service Special Scientific Report: Fisheries 246.

Ehrenfeld, D. 1981. The arrogance of humanism. Oxford University Press, New York.

Erkkila, L. F., B. R. Smith, and A. L. McLain. 1956. Sea lamprey control on the Great Lakes 1953 and 1954. U. S. Fish and Wildlife Service Special Scientific Report: Fisheries 175.

Frazer, N. 1992. Sea turtle conservation and halfway technology. Conservation Biology 6:179–184.

GAO (General Accounting Office). 2001. Invasive species: obstacles hinder federal rapid response to growing threat. GAO Report to Congressional Requesters, GAO-01–724, Washington, D.C.

Hilgert, P. J. 1992. Evaluation of a graduated electric field as a fish exclusion device. Report to Puget Sound Power and Light Company. Beak Consultants, Kirkland, Washington.

Kaopodis, E., E. M. Moon, and L. Hanson. 1994. Sea lamprey barriers: new concepts and research needs. Report of an alternative control research workshop held in Minneapolis, Minnesota, 11–13 February 1994. Great Lakes Fishery Commission, Ann Arbor, Michigan.

McLain, A. L. 1957. The control of the upstream movement of fish with pulsated direct current. Transactions of the American Fisheries Society 86:269–284.

McLain, A. L., B. R. Smith, and H. H. Moore. 1965. Experimental control of sea lampreys with electricity on the south shore of Lake Superior, 1953–60. Great Lakes Fishery Commission Technical Report 10.

Meffe, G. K. 1992. Techno-arrogance and halfway technologies: salmon hatcheries on the Pacific coast of North America. Conservation Biology 6:350–354.

Moyle, P. B., H. W. Li, and B. A. Barton. 1986. The Frankenstein effect: impact of introduced fishes on native fishes in North America. Pages 415–426 *in* R. H. Stroud, editor. Fish culture in fisheries management. American Fisheries Society, Bethesda, Maryland.

Palmisano, A. N., and C. V. Burger. 1988. Use of a portable electric barrier to estimate chinook salmon escapement in a turbid Alaskan river. North American Journal of Fisheries Management 8:475–480.

Reynolds, J. B. 1983. Electrofishing. Pages 147–164 *in* L. A. Nielsen and D. L. Johnson, editors. Fisheries techniques. American Fisheries Society, Bethesda, Maryland.

Sharber, N. G., and J. Sharber-Black. 1999. Epilepsy as a unifying principle in electrofishing theory: a proposal. Transactions of the American Fisheries Society 128:666–671.

Snyder, D. E. 1992. Impacts of electrofishing in fish. Report to the U.S. Department of Interior, Bureau of Reclamation, Salt Lake City, Utah, and Glen Canyon Environmental Studies Aquatic Coordination Team, Flagstaff, Arizona. Colorado State University, Larval Fish Laboratory, Fort Collins.

SRI (Smith-Root, Inc.). 1990. GFFB electrical fish barrier operation and maintenance manual. Report prepared for Salt River Project, December 1990. SRI, Vancouver, Washington.

SRI (Smith-Root, Inc.). 1991. IAE-16 Manual. SRI, Vancouver, Washington.

Sternin, V. G., I. V. Nikonorov, and Y. K. Bumeister. 1976. Electrical fishing, theory and practice. Keter Publishing, Jerusalem.

Swink, W. D. 1999. Effectiveness of an electrical barrier in blocking a sea lamprey spawning migration on the Jordan River, Michigan. North American Journal of Fisheries Management 19:397–405.

USFWS (U.S. Fish and Wildlife Service). 1994. Transportation and delivery of Central Arizona Project water to the Gila River basin in Arizona and New Mexico. Final Biological Opinion to the U.S. Bureau of Reclamation, 2–21-90-F-119, Phoenix, Arizona.

USFWS (U.S. Fish and Wildlife Service). 2001. Transportation and delivery of Central Arizona Project water to the Gila River basin in Arizona and New Mexico and its potential to introduce and spread nonnative aquatic species. Revised Final Biological Opinion to the U.S. Bureau of Reclamation, 2–21-90-F-119a, Phoenix, Arizona.