EFFECTIVENESS OF ELECTRICAL FISH BARRIERS ASSOCIATED WITH THE CENTRAL ARIZONA PROJECT, 1988-2000

Prepared for

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Abstract.–-The Central Arizona Project (CAP) canal is an aqueduct that delivers Colorado River water into the Gila River basin. During planning and construction, issues arose regarding unwanted entrainment and transport of non-indigenous fishes and other aquatic biota into, through, and out of the canal. One control strategy was emplacement of electrical fish barriers on two CAP distributary canal systems to prevent fishes from moving upstream into Gila River basin surface waters. The operation, maintenance, and effectiveness of these barriers is described for the period 1988-2000. Documented outages totaled more than 100 hours, representing <0.001% down time since installation. It is nearly certain that outages allowed transgressions by undesired fish(es). A few exceedences when barriers were operating according to design criteria suggest they may not totally block passage of upstream migrating fish. 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 (necessary to document outages and understand potential for undocumented barrier outages) totaled more than 400 days, representing about 3% of the period of barrier operations. Complexity of electrical barrier systems and 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 determine cost effectiveness of such refinements.

INTRODUCTION

Use of electric fields to prevent upstream movements of fishes was initially applied in North America in large scale to sea lamprey *Petromyzon marinus* control efforts in the Great Lakes in the 1950s (Applegate et al. 1952, Erkkila et al. 1956, McClain 1957, McClain et al. 1965). The goal of that program was to prevent sea lamprey depredation on declining stocks of lake trout *Salvelinus namaycush* by blocking lamprey spawning migrations in streams tributary to the Great Lakes. Electrical barriers were installed on streams considered inappropriate for low-head barriers that served a similar function. The electrical barrier program for the most part successfully achieved its goals until abandoned in 1960 when application of the selective lampricide 3-triflouromethyl-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 also have been applied to solve other fish control problems, including escapement estimation (Palmisano and Burger 1988) and prevention of entrainment (Burrows 1957, Barwick and Miller 1996). Information on much of these uses is largely hidden among gray literature reports, and most relates only to effectiveness of barriers on short-term fish control goals, i.e., little is available on long-term system reliability.

During planning and construction of the Central Arizona Project (CAP), a 540-km aqueduct that delivers Colorado River water from Lake Havasu on the AZ-CA border into the Gila River basin through central and southeastern AZ, issues arose regarding unwanted entrainment and transport of non-indigenous fishes and other aquatic biota into, through, and out of the canal. Concern was that these organisms could negatively impact both native species and established non-native 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 within the Gila River basin once outside the CAP (FWS 1994, 2001). Where site-specific circumstances warranted (direct connections between CAP waters and Gila River basin surface waters, and insufficient gradient available to install low-head barriers), electrical fish barriers were constructed to prevent such movements.

I describe the operation, maintenance, and effectiveness of electrical fish barriers in preventing upstream movements of fishes in central Arizona canal systems during 1988-2001. 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. I also briefly describe the development of standard operating procedures (SOP) that detail outage response scenarios for the electrical barrier systems. Information on 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 to refine current operations.

Study Sites

Two electrical barriers were constructed in 1998 on Salt River Project (SRP) Arizona (AZ) and South (SO) canals upstream of the CAP-SRP interconnect downstream from Granite Reef Diversion Dam (GRDD) on the Salt River (Figure 1). These canals transport Salt River surface water diverted at GRDD to metropolitan Phoenix, AZ, for municipal, industrial, and agricultural uses. Electrical barriers were intended to prevent movements of fishes from the CAP, through the SRP system, and into the Salt and Verde river systems upstream. At the electrical barrier sites, AZ Canal is 18.5 m wide, and SO canal is 15.8 m wide. Maximum depths in both canals are approximately 2.5 m in these areas. Both are concrete-lined and steep-sided. Recent flow volumes over the electrical barriers were near 587,000 and 400,000 acre-ft per annum, respectively, with maximum rates near 1,200 ft^3/s.

Another electrical barrier was installed in 1990 on the San Carlos Irrigation Project (SCIP) Pima Lateral Canal (PLC) above a CAP-SCIP interconnection (Figure 2). This barrier was to prevent CAP fishes from entering Florence-Casa Grande Canal (FCGC) and moving upstream past Ashurst-Hayden Diversion Dam (AHDD) to Gila River, San Pedro River, and Aravaipa Creek, the last inhabited by federally-threatened native fishes. The concrete-lined PLC is 24.5 km downstream from AHDD, and transports approximately 134,000 acre-ft per annum at a maximum rate of 660 ft^3/s.

Soon after the electrical barrier on PLC was constructed, turnouts from CAP to upstream portions of FCGC were proposed, rendering the PLC barrier ineffective. Thus another barrier was placed later in 1990 on FCGC at China Wash 4.2 km downstream from AHDD (Figure 2). Florence-Casa Grande Canal is unlined, and carries approximately 307,000 acre-ft per annum at a maximum rate of 1,265 ft^3/s. Canal dimensions vary from 15-30 m wide, with an average depth of 1 m. As the barrier on PLC was considered redundant, it was taken offline in 1992.

Methods

Electrical Barrier Design---Electrical fish barriers installed in SRP and SCIP systems were designed by Smith-Root, Inc. (SRI), and incorporate seven major elements: direct current pulse generators, electrodes on weir structures, electrical cables connecting pulse generators and electrodes, emergency backup generators, weirs across the bottoms of canals to hold electrodes, electronic remote monitoring of barrier conditions and alarm status, and SOP manuals developed specifically for each system that details contingency actions in the event of 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. 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; strength increases with proximity to electrodes. Pulse width is 25 ms at 2 pulses/s, although the system is adjustable to between 8-32 ms duration at 1-13 pulses/s. Barriers are powered by 240 volt, 75 KVA single phase power transformers (SRI 1990).

In the event of power failure, an automatic transfer switch starts a 50 KVA 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 timing to synchronously trigger 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 master pulse generator (SRI 1990).

Electric field lines are purported to extend evenly from bottom to top of the water surface (SRI 1990), and run parallel to flow, i.e., fish attempting to swim upstream are oriented head-to-tail along the maximum power gradient. Redundancy in the pulsators allows failure of one or more without compromise of the entire barrier, and allows 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) a platform for electrode installation, 2) assure a uniform water depth to improve barrier efficiency, and 3) increase water velocity over the barrier by reducing 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).

Electrodes in SRP canals are high carbon steel railroad rails. Electrodes installed in FCGC and PLC were 1-in diameter stainless steel rods, but the lower five electrodes at FCGC were replaced with railroad iron in 1999. The seven electrodes at each barrier are evenly spaced at 1-m intervals, and voltages from the six pulse generators are applied between successive pairs of electrodes.

Salt River Project and SCIP 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 pre-programmed phone numbers at various intervals until the alarm is acknowledged. In addition to reporting status of the six pulse generator outputs, status of several additional conditions were monitored, e.g., main power, auxiliary power, etc. The system also initiates weekly reports that are phoned to SRI.

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

Monitoring Records---SRI conducted quarterly site inspections to monitor operation and condition of the barrier systems and their components. Monitoring consisted of measurements of voltages through the electrode arrays, *in situ* electrical field strengths, water conductivity, pulse generator output levels, remote alarm conditions, auxiliary generator crank tests, and various "routine" inspections (e.g., generator battery water levels, generator fuel and oil levels). SRI generated and distributed quarterly reports summarizing these data, that form the basis of a portion of the information presented here.

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

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

Finally, when unusual events at electrical barriers warranted, correspondence among SRI, SRP, SCIP, and USBR that discussed barrier operations, maintenance, and monitoring also provided important information for this report, as did site visits by the author.

Results

Barrier Operations and Effectiveness

Electrical fish barriers on SRP SO and AZ canals went online in November 1988, and remote monitoring of barrier operations began in January 1992. Operational histories prior to 1992 were based on maintenance inspection reports, and no outages during that period were recorded by SRI (D. Fuller and M. Thurnhofer, SRI, personal communication).

The electrical fish barrier on PLC was constructed in late 1989, and went online prior to first delivery of CAP water down the PLFC in April 1990. The electrical barrier on FCGC at China Wash was constructed February-April 1990, and went online in May 1990. As the electrical barrier on PLC became redundant following operation of the barrier at China Wash, it was shut down in May 1992. Thus two electrical barriers were operational during the period May 1990 through April 1992. Prior to the January 1992 installation of SRI remote monitoring systems, barrier effectiveness was determined by physical inspections and preventative maintenance of barrier components.

The first documented barrier outage occurred on PLC on 2 June 1990, when it was disabled for a period of 12-36 h following disconnection of primary power to the barrier by an unauthorized person(s) and the auxiliary power generator operated until it ran out of fuel (Table 1). 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 PLC 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 AZ Canal following loss of primary power and failure of the battery that powered the backup generator (Table 1). This outage lasted 2 h 16 min. Although backup generator batteries at all electric barrier sites were equipped with continuous trickle charging systems, apparently in this case the battery lost capability to hold a charge. Policy was subsequently instituted to exercise batteries monthly (and later weekly) using backup generators, and batteries routinely were to be replaced at 2-yr intervals (see below). SRP has since added remote monitoring of auxiliary generator battery voltages.

Consequences of this outage were soon apparent, as several grass carp *Ctenopharygodon idella*, a non-native species stocked by SRP downstream of the electrical barriers for weed control but not previously found above, were captured above the barrier during subsequent fish monitoring. As public access to SRP canals above the electrical barriers is prevented by high fencing, it is unlikely these fish were moved by humans. No fish species have yet been found below the electrical barrier on FCGC that do not also occur upstream.

A suspected barrier outage on SO Canal on 2 September 1994 was apparently caused by a lightning strike that damaged several pulse generators (Table 1). 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. SRI reported the barrier "mostly operational" during this period.

At least 9 additional documented electrical barrier outages resulting from failures of backup generators to power the barriers following primary power disruptions occurred between 1995 and 1998, all but one occurring at the China Wash facility (Table 1). 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 "over run" errors (3). To my knowledge, 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 have been proposed.

On 23 July 1999, pulse generators 1, 4, and 6 on AZ 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 master. Thus the barrier was not functional during this period (Table 1). Lightning apparently caused similar damage to SO 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, SRI considered the barrier "fish-tight," but the event is noted here as a possible barrier outage (Table 1).

The most recently documented outage of SRP or SCIP electrical fish barriers occurred at SO Canal during the 29 November 1999 rewatering operation following a routine canal "dry-up" (Table 1). In this instance, the canal was partially rewatered prior to the barrier being electrified. Duration of this outage was undetermined. Better definition of canal dewatering and rewatering scenarios in SOPs has been recommended to prevent future similar occurrences.

Capture of two grass carp above the SO 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 SRI's remote monitoring system occurred prior to that time, but SRP's remote monitoring was functional during that period, and it did not report alarms other than routine. SRI 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 AZ Canal in absence of prior known barrier outages support this theory. SRP records show there was a several week period in 2000 when flows into the canal (and over the electrical barrier) from GRDD were low. A vertical steel plate 13 cm high was emplaced across the width of the weir at the AZ Canal barrier in 2001 to present additional obstacles to fishes attempting to swim upstream during low flow conditions. A similar device was recently incorporated at the China Wash barrier, and one is planned for the SO Canal barrier.

In October 1999, I released approximately one dozen red shiner *Cyprinella lutrensis* into the middle of the electrical field of the China Wash 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

Table 2 lists proximate causes of monitoring outages at SRP and SCIP electrical fish barriers that lasted more than 24 h; scores of shorter outages resulting from unique events or intermittent problems are not listed. Causes of remote monitoring outages were highly variable, ranging from simple human error to complete system failure. Causes of several long-term outages were undetermined, as were most intermittent outages.

Standard Operating Procedures Development

SRP Barriers---The first SRP SOP manual was developed in early 1990, and it described the AZ and SO Canal electrical barrier systems, their inspection procedures, and emergency operating procedures. The latter section provided timetables for specific actions to be taken in event of any of six failure scenarios, which ranged from failure of 1 or 2 pulse generators (barrier remains "fish tight") to complete system failure (barrier not effective). This SOP allowed up to 8 hours of system failure prior to requiring initiation of corrective actions.

The SRP SOP was revised twice in 1991, first to include SRI's Electrical Barrier Operation and Maintenance Manual, maintenance checklists, notification procedures, and revised corrective actions to be taken in event of barrier failure, and then to provide quarterly inspection reports to

USBR. Barrier failure scenarios were tightened to require immediate corrective action responses by technicians.

Revision of the 1991 SRP SOP was initiated following discovery of two grass carp above the electrical barrier on AZ Canal in January 1994. Several improvements to the maintenance program were incorporated into the SOP, and it added 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.

SCIP Barriers---The first SOP submitted by SCIP for the PLC and China Wash barriers was in early 1991, which was modeled after the 1990 SRP SOP. In late 1991 and early 1992, the SCIP SOP was revised to include increased inspection frequencies, maintenance of inspection records, addition of emergency contacts, and a provision that gates on AHDD to FCGC be shut if sufficient operating power cannot be provided to the barrier within 3 hours after initial shutdown.

Discussion

Barrier Outages

Known outages of electrical fish barriers on SRP and SCIP canals totaled more than 100 hours, representing <0.001% down time since installation. Although this proportion is small, it is nearly certain it was sufficient to allow transgressions by undesired fish(es). Management agencies that called for emplacement of electrical barriers to protect existing native and sport fisheries from downstream contamination appeared to accept they likely would not be 100% effective, but the barriers were designed and built to "totally block the passage of upstream migrating fish" (SRI 1990).

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 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.

A recurring source of failure of electrical barriers in central Arizona was a result of lightning strikes. 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 lightning protection measures have been recommended by the barrier manufacturer, but only a few have been implemented.

In addition to known barrier outages that ostensibly allowed breaches of the barriers by fish(es), it is nearly certain that at least one species (grass carp) successfully transgressed the electrical barriers on SRP canals during periods without a known history of electrical outage, based on 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 SRP canals that is not also resident above. The other species, striped bass *Morone saxatilis*, remains rare in catches from SRP canals, and it has not been recorded from above the electrical barriers (unpublished data). There are no species from the FCGC system that have similar distributions from which a barrier exceedence could be easily detected.

Transgressions of grass carp over SRP 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. SRI's explanation for such occurrences, which have been suspected at other SRI electrical barrier facilities (D. Smith, SRI, 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 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, addition of low vertical obstacles across barrier weirs in theory should prevent future transgressions of large-bodied fishes via this avenue.

The anecdotal observation that red shiner released into the electrical field at the China Wash barrier failed to tetanize as expected is bothersome. 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 (SRI data), and voltage settings on the pulsators are maximized (B. Moorhead, SRP, personal communication). The 1 V/cm datum is higher than threshold values producing tetany via pulsed DC current 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.

Small fish are less affected by an electric field due to 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, SRI, personal communication). I note, 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.

Remote Monitoring and Standard Operating Procedures

Known outages of the remote monitoring systems totaled more than 400 days, 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 total barrier failures had occurred, it could not be determined with certainty that they did not. In most cases it was not possible to verify durations of barrier outages with alarm monitoring reports provided by the barrier manufacturer. Remote monitoring data are absolutely necessary to document barrier failures and identify outage causes.

Development and refinement of standard operating procedures manuals appears invaluable in reducing and documenting sources of barrier failures. Review of these procedures by management agencies 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).

Conclusions

Unforseen environmental problems that inevitably arise following human alterations of natural systems often require bioengineering solutions, or at least many believe they can be solved through application of such technology (Ehrenfeld 1981; Meffe 1992). And often bioengineering "solutions" cascade to further applications of technology to solve problems created by their initial (and subsequent) application. In the present case, construction of large mainstem dams to control hydrology of the Colorado River fostered introductions of non-native sport fishes (and their associated biota) for recreation. Operation of the CAP to deliver Colorado River water to interior Arizona transports non-native biota into the Gila River basin, where they can negatively impact the basin's native fishes and established sport fisheries. Installation of electrical fish barriers on CAP distributary canals was intended in part to prevent this effect.

Yet complexity of electrical barrier systems and 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 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 installation of the original systems in the late 1980s. However, entities responsible for operation and maintenance of barriers have been hesitant to shoulder such expensive component replacements. Management agencies must determine whether such upgrades will be cost effective and compulsory.

In the final analysis, CAP electrical barriers are halfway technologies (Frazer 1992) that cannot solve the ultimate problem of omnipresence of non-native 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 effectiveness.

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TABLE 1. Known outages of electrical fish barriers on Salt River Project (SRP) and San Carlos Irrigation Project (SCIP) canals, 1988-2000. There were no outages prior to January 1990 based on site maintenance inspections performed by Smith-Root, Inc. (SRI); history since January 1990 is based on remote monitoring records provided by SRI and SRP. Acronyms as follow: PL=SCIP Pima Lateral Canal, CW=SCIP Florence-Casa Grande Canal at China Wash; AZ=SRP Arizona Canal, SO=SRP South 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	CW	1 h 15 min	Backup generator fuel supply turned off	Fuel supply turned back on
23 Aug 1996	CW	2 min	Generator start-up problems	Not documented
2 Sep 1997	CW	2 min	Backup generator failure	Not documented
8 Sep 1997	CW	14 min	"Fuel interruption" to backup generator	Not documented
12 Sep 1997	CW	6 min	Backup generator failure	Not documented
28 Aug 1998	CW	1 h	Backup generator controller "over run" errors	Not documented
4 Sep 1998	CW	1 h 30 min	Backup generator controller "over run" errors	Not documented
23 Sep 1998	CW	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 SOP modifications

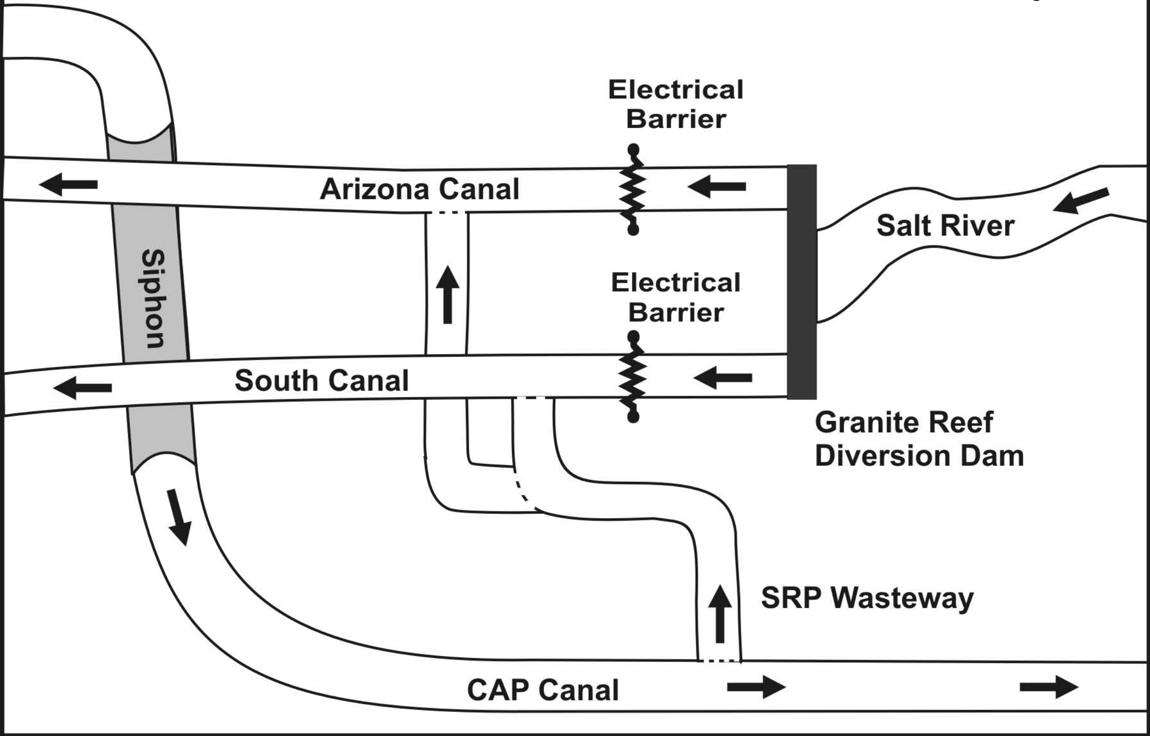
TABLE 2. Outage history of remote monitoring systems of electrical fish barrier on Salt River Project (SRP) and San Carlos Irrigation Project (SCIP) canals, 1990-2000. See Table 1 for acronyms.

Date	Site	Duration	Cause	Remedy
11 May 1992	CW	2 d	Bad modem chip	Modem chip replaced
22 Aug 1994	CW	8 d	Memory corrupted	Restored settings
2 Feb 1995	CW	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 CW	28 d	Incompatible modem upgrade	Original modem restored; software upgraded for new modem
1 Apr 1996	CW	<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	CW	undetermined (<8 d)	Undetermined	Reset the system
6 Jan 1997	CW	21 d	Component card failure	Replaced card and other system components
29 Sep 1997	CW	10 d	Undetermined	Not documented
8 Oct 1997	CW	20 d	Modem module failure	Total system replacement
19 Nov 1997	CW	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 (SRI inspection report, 21 Nov 1995).

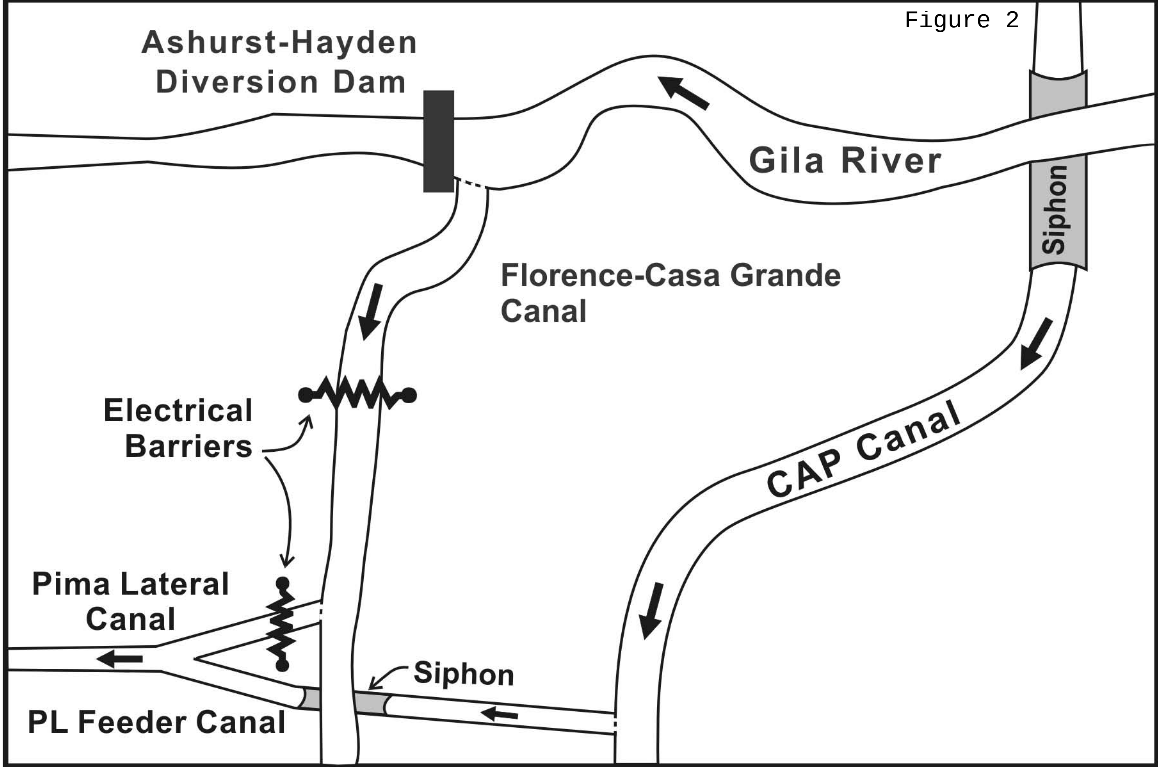
List of Figures

Figure 1



Electrical Barrier
Arizona Canal
Salt River
Siphon
Electrical Barrier
South Canal
Granite Reef Diversion Dam
SRP Wasteway
CAP Canal

Figure 2


Ashurst-Hayden
Diversion Dam
Gila River
Siphon
Florence-Casa Grande
Canal
Electrical
Barriers
CAP Canal
Pima Lateral
Canal
Siphon
PL Feeder Canal